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Review Article

CHALLENGES AND OPPORTUNITIES TO DESIGN FUTURE CROPS: GATEWAY TO SUSTAINABLE AGRICULTURE IN 21ST CENTURY

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Abstract *The global food production system is facing numerous challenges due to factors such as population growth, climate change, limited resources, and environmental preservation. To address these challenges, various strategies can be employed to develop future crops that are more productive, nutritious, and resilient. One strategy is to improve the yield potential of existing crops by developing new high-yielding cultivars. This can be achieved through the development of new varieties that can produce more grain under optimal conditions. Additionally, improving the nutritional quality of crops is important to address nutrient deficiencies. Synthetic biology and metabolic engineering methods can be used to develop crops with enhanced nutritional value. Efficient utilization of agricultural resources is another important aspect of crop improvement. This includes developing crops that use water and nutrients more efficiently, reducing the need for irrigation and fertilizers, and minimizing environmental impacts. Increasing the resistance of crops to pests, diseases, and extreme weather events can also help reduce the use of pesticides and minimize crop losses. The domestication of wild or semi-wild plants through genetic manipulation offers new opportunities for crop design. These plants may have high nutritional value, stress tolerance, and specialized metabolites that can be incorporated into cultivated crops. Similarly, the domestication of orphan or neglected plants can contribute to crop improvement by incorporating unique traits. Genetic improvement through the transfer of genes from wild relatives or other species can also enhance crop productivity. Advancements in genomics and genetic technologies can aid in the identification and transfer of beneficial alleles. Agronomic improvements, such as maximizing the effectiveness of crop protection agents and fertilizers while minimizing their environmental impact, can also contribute to crop performance. The emerging field of synthetic biology offers opportunities for developing novel biological devices and systems that can further enhance crop productivity and resilience. Overall, these strategies can help address the challenges faced by the global food production system.*

Keywords: *crop improvement strategies; sustainable agriculture; climate change; food security*

Introduction

Current food production systems face enormous pressure to boost yield to feed the world's growing population. The yields of wheat, rice, maize, and soybeans have grown at an annual rate of about 1%, which is less than the 2.4% increase in yields that would be required to double global production (Lowenberg-DeBoer et al., 2020). A significant challenge to the global food production system is the impact of climate change. According to Ranjbar & Pirasteh-Anosheh (2015), for every degree Celsius that the global mean temperature rises, the yields of the aforementioned crops will decrease globally. Importantly, to meet the requirement for ecosystem preservation, this massive increase in food production must be achieved with constrained or depleted land resources and water systems

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(Poehlman, 2013). According to Peltonen-Sainio et al. (2009), there is a possibility that a rise in the frequency of extreme weather events will impact pest and disease dynamics and debilitate plant resistance.

The 21st century's challenges

There is a common assumption in the West that food is adequate in almost every regard. Other variables that contribute to scarcity and hunger include political systems, poverty, violence, and insufficient distribution. However, as the twenty-first century comes to a close, several challenges will arise in maintaining the essential level of food production. One of these is that by 2020, the world's population will exceed 8 billion. Other contributing factors include:

- the trend toward higher meat consumption in wealthier societies, which increases agricultural output per capita
- the adverse effects of climate change, such as more frequent and intense climate fluctuations and a higher probability of crop failures
- the severe constraints on the amount of land available
- the scarcity of water required for irrigation to support crop development
- and the requirement to prevent environmental degradation.

Depending on these characteristics, future estimates range from pessimistic to optimistic. When things do not go as planned, negative projections are usually thought to be the more likely outcome. Crop plants meet a substantial percentage of our food demands, so crop research's capacity to overcome the aforementioned challenges will be critical to the field's long-term success. This finding paves the way for the development of crop enhancement technologies, which will be described in greater detail in the following sections.

Strategies to develop future crops.

Enhancement of presently cultivated crops

The first simple technique for developing future crops that meet sustainable agriculture requirements is to improve the following elements of existing well-cultivated crops. The most cultivated crops are shown in Figure 1.

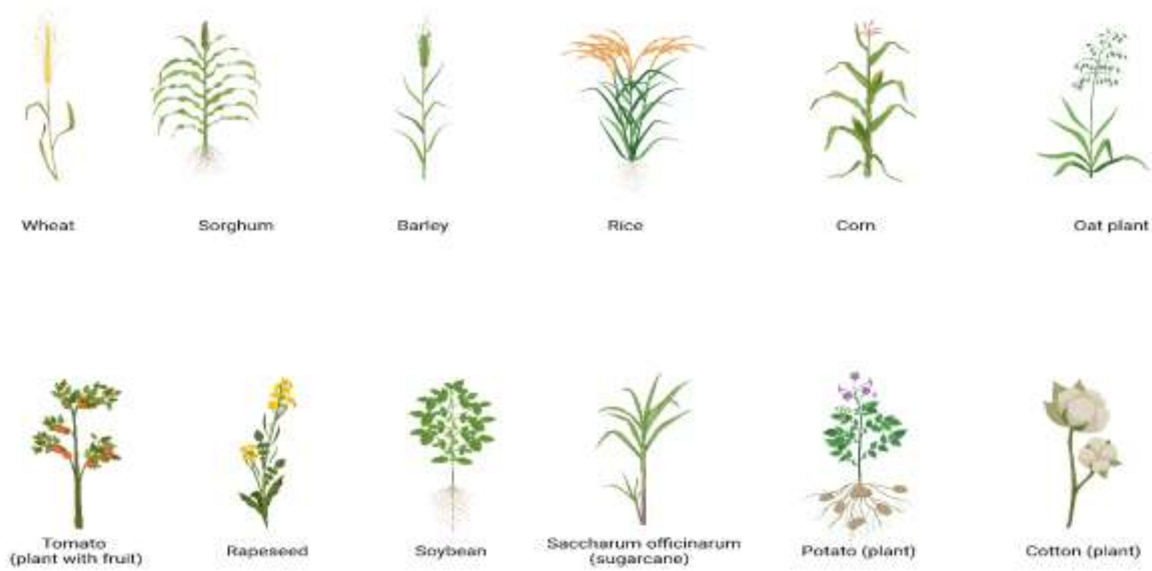

Figure 1: The most cultivated crops around the world

Yield enhancement

It is projected that substantial crop yields will need to improve at a rate of 2.4% every year to meet the world's food needs by 2050. Conversely, Van Camp (2005) stated that the current rates of growth for the four main crops—soybeans (*Glycine max*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), and maize (*Zea mays*)—are only around half of what is predicted. The Future Crops Design initiative's main goal is to develop new, high-yielding cultivars to fill this gap. According to a demonstration by Liu et al (2020a), a super-high-yield rice variety may produce one to three times as much grain in optimal conditions as it could in traditional paddy fields.

Nutritional quality enhancement

Hidden hunger has persisted in spite of substantial progress in food accessibility during the past half-century, as a result of alterations in human lifestyles and consumption patterns (Blum, 2009). Cereal crops have more worth for nutritional value in human health diet (Figure 2). Illustratively, daily vitamin A deficiency affects 17–30% of infants below the age of five in America and Sub-Saharan Africa (Farid et al., 2023). It is estimated that two billion individuals worldwide suffer from chronic micronutrient deficiencies, presenting a novel peril to human well-being. In addition, over the past decade, there has been a substantial rise in the incidence of type-2 diabetes, obesity, and colon diseases (Testa et al., 2016). The subsequent objective of the Future Crops Design initiative is to generate crops that possess enhanced nutritional value or specialized metabolites through the application of synthetic biology and metabolic engineering methods (Dey et al., 2004).

Figure 2: Nutritional value chart for important cereal crops

Nutritional values/Crops	Rice (Brown)	Maize	Wheat	Barley	Oat	Rye
Energy (kcal/100 g)	357	357	310	360	388	298
Macronutrient (g/100 g)						
Carbohydrate	76.2	74.3	71.2	73.4	66.3	75.9
Protein	7.5	9.4	12.6	12.5	16.9	10.3
Fat	3.2	4.7	1.5	2.3	6.9	1.6
Dietary fiber	3.6	7.3	12.2	17.3	10.6	15.1
Minerals (mg/100 g)						
Calcium	33	7	29	33	54	24
Iron	1.80	2.71	3.19	3.60	4.72	2.63
Magnesium	143	127	126	133	177	110
Phosphorus	264	210	288	264	523	332
Potassium	268	287	363	452	429	510
Sodium	4	35	2	12	2	2
Zinc	2.02	2.21	2.65	2.77	3.97	2.65

Source: USDA National Nutrient Database for Standard Reference, Release 20

Improving the effectiveness of agricultural resource usage

Since 1945, inefficient agricultural management has reduced arable land output by approximately 17% (Kloepper et al., 2004). Khan et al. (2024) discovered that modern crops only use roughly 45% phosphorus and 30-50% nitrogen fertilizer. Furthermore, the availability of freshwater is becoming a major impediment to agriculture in many places of the world. Without irrigation, crop yield is predicted to fall by about 20%, requiring an estimated 2800 km3 of fresh water per year (Shimono et al., 2009). We should strive to develop crops that use water and nutrients efficiently while maintaining productivity to reduce agricultural input requirements and environmental commitments.

Increasing resistance to biotic and abiotic stress

Reducing pesticide use is essential to developing sustainable agriculture. It may be possible to significantly lower crop production losses and environmental contamination by introducing cultivars with increased resistance to viruses and diseases (Kettlewell et al., 2010). Furthermore, considering the significant increase in the frequency of extreme weather events over the last ten years, it is essential to strengthen the resilience of important crops against abiotic stresses (Morales et al., 2020; Vergine et al., 2017). It may be beneficial for agriculture to modify crops so they are resistant to a particular type of abiotic stress in marginal lands, where the soil is unstable and cannot support the growth of high-yield crops (Sturz & Nowak, 2000).

De novo *domestication*

Meyer and Purugganan define domestication as a human-initiated process that consists of four stages: the beginning of domestication, the fixing of desired alleles, the creation of cultivated populations, and selective breeding. The global food supply is becoming more uniform due to the promotion of Green Revolution technology (Anderson et al.,

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2005). There is a genetic variety difficulty for modern agriculture since there is a greater likelihood that plants will not be able to adjust to unexpected environmental changes in the future and that their genetic makeup would encourage the return of diseases. Hence, de novo domestication of wild or semi-wild plants through genetic manipulation of homologous domestication genes opens up new possibilities for crop design in the future and improves existing cultivated types.

Domestication of orphan or neglected plants

A phase of semi-domestication was experienced by several wild species, such as millet, during the history of agriculture. But eventually, as other important crops evolved more quickly, they were abandoned (Sreevidya et al., 2016). Undoubtedly, a larger number of wild plants remain mostly unknown to the general public and have not seen considerable artificial selection. These plant species are often referred to as "orphan" plants. Even though they are not very productive and are not good for large-scale production, semi-domesticated and orphaned plants have some benefits, such as high nutritional value, great stress tolerance, and a lot of specialized metabolites. To create stress-tolerant cereals with high yield potential, naturally stress-tolerant orphan plants have been proposed as a major germplasm resource (Wu et al., 2019).

Many types of cereals have domesticated traits in common. A set of phenotypic traits known as "domestication syndrome" developed throughout the domestication process and helped to distinguish grains from their wild ancestors (Kandhro et al., 2014). Surprisingly, a growing amount of research suggests that the domestication syndrome is caused by ubiquitous and convergent mechanisms (Edgerton, 2009). For example, orthologs of the Waxy gene control sticky grain enhancement traits in barley, millet, rice, and sorghum (Nguyen et al., 2021). Similarly, the stay-green gene G regulates seed dormancy in several species, such as soybean, rice, and Arabidopsis (Lei et al., 2024). In light of these conceptual advancements, a great deal of emphasis has been focused on the de novo domestication of wild or semi-wild plants into innovative complementary commodities (Elkeilsh et al., 2019). Quinoa, or Chenopodium quinoa, is a very nutritious food. Quinoa seeds are free of gluten and have a low glycemic index. They are also a good source of fiber, lipids, vitamins, minerals, and essential amino acids. Given the spread of the quinoa genome and the development of a tissue culture method, expanding the domestication of current quinoa cultivars would represent an inventive way to produce nutrient-dense food and a significant contribution to global food security (Mishra et al., 2021).

Over the previous 20 years, there has been a significant increase in demand for quality natural rubber. It is now not practicable to increase the production of natural rubber from the rubber tree (Hevea brasiliensis L.) because of its small cultivation area, narrow genetic background, vulnerability to severe infections, and labor-intensive labor requirements. The rubber dandelion (Taraxacum kok-saghyz), which produces natural rubber of equivalent or higher quality (van Beilen and Poirier, 2007; Cherian et al., 2019), has been selected as a possible candidate for de novo domestication to meet the need for natural rubber (Adams & Erickson, 2017).

Domestication of perennial crops

In contrast to the perennial nature of the overwhelming majority of plants in nature, cereals, oilseeds, and legumes—which comprise the majority of the world's food supply—are grown annually (Kumar et al., 2011). Annual crops often exhibit reduced fertility and water absorption capacities, in addition to a propensity for causing soil disturbance and water system harm through the leaching of nitrates and pesticides. This is because their root systems are shorter and less extensive, necessitating yearly sowing (Saikia et al., 2012). In contrast, perennial crops exhibit extended growth cycles, robust root systems, and efficient water and nutrient utilization, while also withstanding a range of adversities (Kiran et al., 2022). Moreover, annual plants are incapable of sequestering carbon from the soil like perennial plants. As a result, there is a growing endorsement for the implementation of varied and extended grain-cropping systems as a significant approach to promoting sustainable agriculture (Ray et al., 2013). Through outcrossing with analogous natural species, annual cultivars are transformed into perennial varieties of wheat, maize, and sorghum, respectively. Perennial crop development necessitates enhancements in various aspects, including but not limited to food quality, nutrient utilization efficiency, flowering duration, seed size, and quantity, and dormancy (Ray et al., 2012). Although perennial plant yields remain modest when semi-domesticated or undomesticated, it is anticipated that artificial selection and effective agricultural management will significantly increase production (Zhao et al., 2024).

Re-domestication of current cultivated crops

To satisfy human needs, traits must be carefully chosen during the domestication process. Domesticated cereals often have better and more distinguishing qualities than their wild counterparts. For example, compared to cultivated soybean seeds, natural soybean seeds have higher oil content and less protein (Ibrahim et al., 2021). Domestication has been a dynamic process throughout history. Redomination is the process by which established

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crops or their offspring are exposed to new artificial selection pressures, changing their evolutionary course to suit new demands from humans (Haroon et al., 2022). Reverting the current oil-rich soybean crop to a high-protein variety could be one way to address the issue of the restricted supply of animal feed. Similar efforts have been made to support the restoration of maize's ability to produce the oil-based compounds known as oleic acids (Saritha et al., 2020).

Enhancement of crop productivity through genetics Moving genes around

A crop's performance can also be genetically improved by introducing superior alleles at already-existing loci by traditional crossing using markers and other technologies, in addition to adding new loci through transformation. Currently, transformation cannot be used to replace alleles at pre-existing loci, but antisense or co-suppression constructs can be used to suppress gene expression at pre-existing loci (Zhao et al., 2024).

Since the first converted plants were discovered in 1983, significant progress has been made in the ability to convert crop plants. However, additional technological progress is required to increase the number of genes that can be transferred, maximize the frequency of transformation, allow for more accurate control over the expression of the transferred genes, and permit targeted gene insertion. Given the recent record of accomplishment, there are many reasons to be hopeful that a sizable amount of the required goals will be met (Schaart et al., 2016).

Sources and nature of genes.

As previously stated, tremendous progress has been achieved in identifying and transferring alleles from wild relatives of crops that may improve agricultural yield into germplasm that has been modified. This is anticipated to act as a significant catalyst for the creation of novel crop cultivars that employ genetic material sourced from a diverse range of crop relatives. Any species' genes can be incorporated into crops through transformation, and microbe-derived genes were employed to produce the first goods that were sold commercially that were resistant to pesticides or insects. Not every gene that was used was a precise duplicate of the genes found in the microorganism; in one case, the entire gene had to be synthesized in a lab to produce the same protein sequence as an insect toxin cleaved from the same gene by *Bacillus thuringiensis* (Zhang et al., 2021).

Even with the wide range of genes in the biological world and the great diversity of crops and their offspring, the basic difference can sometimes appear to be absent. This constraint can be overcome by utilizing a variety of biochemical engineering techniques. Bread can be made by using enzymes with altered active sites or wheat storage proteins whose structural changes impact their ability to create disulphide cross-linkages. More advanced techniques have been and will be developed to help drive the development of new genes in bacteria or test tubes for use in plants. One such technique is phage display technology, which produces distinct antibodies (Ahmad et al., 2019).

Up until now, the main goal of crop transformation has been to increase crop protection by making crops more resistant to insects or broad-spectrum herbicides. Furthermore, genes that control quality traits such as fruit maturation, the makeup of oil fatty acids, and starch properties have been introduced. More research is required to achieve more complex traits, such as resistance to a broad range of diseases; this may necessitate manipulating a sizable number of genomes to get the desired changes. While there is a vast array of structural genes that can encode a wide variety of proteins, there are currently very few promoters and regulators available to ensure that the genes are consistently expressed during the appropriate developmental stages and in the appropriate organs and tissues. Furthermore, a far better understanding of the operation and mutability of complex regulatory and signaling pathways is desperately needed. Research on the possible advantages of crop enhancement through transformation is still in its early stages (Grulke & Heath, 2020).

Innovative Technologies in Genomics

We must improve our ability to deeply examine the nucleic acid-based information inside the cell if we are to succeed in genomics-assisted reproduction. It is commonly acknowledged that molecular markers are extremely valuable genetic tools that can be used to create physical and genetic maps, as well as to map features among various crop species (Woodhouse et al., 2021). In reality, the use of these markers in breeding programs has resulted in enhanced varieties and/or superior lines for several temperate cereal species. Studies have indicated that the most effective molecular marker technologies for reproductive applications are microsatellite or SSR (simple sequence repeat) markers. Conversely, new developments in high-throughput genotyping technologies and next-generation sequencing have led to the replacement of single nucleotide polymorphism (SSR) markers by SNP markers, which is predicted to happen in the next five years (Wang et al., 2016).

New Genetic Approaches for Harnessing the Natural Variation

Domesticating plant species for use in food, medicine, or other uses is one of the oldest human endeavors. All the same, domestication or breeding of cereal species has reduced the number of alleles in the gene pool. As a result, access to alleles from the cultivated gene pool is often restricted for breeders, and they are unable to take advantage of the natural

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variation that naturally exists in a species' germplasm collection. Therefore, wild species can serve as a source of advantageous alleles for breeding programs (Hasanuzzaman et al., 2013). However, only a small portion of the genetic variety seen in wild species can be transferred to domesticated ones, which limits the use of traditional breeding techniques. The next section describes several particular techniques for introducing genes from native species into breeding lines (Muchate et al., 2016).

Agronomic improvement of crop performance

Genetic improvement is the main focus of this review due to its significant potential to increase crop output. This is partly explained by the massive yield gains that agronomy and crop protection have already achieved. In the upcoming years, significant progress is expected in these domains, especially about maximizing the effectiveness of crop protection agents and fertilizers while also minimizing their detrimental effects on the environment. Improvements in combinatorial chemistry and the identification of new target sites by genomics research should improve the caliber of agrochemicals available to farmers. Intelligent decision-supporting systems combined with equipment that can carry them out correctly, especially when it comes to water, fertilizer, and crop protection, will certainly boost agricultural standards but may not significantly increase productivity (Ju et al., 2021).

Synthetic biology approaches

The emerging field of "synthetic biology" combines engineering and biological principles to create novel biological devices, parts, or systems. Future crop growth in agriculture could be significantly impacted by this quickly growing field. Phytoremediation was one of the first applications of successful metabolic engineering in plants. For example, overexpression of a secretory laccase in transgenic Arabidopsis plants enables ex-planta phytoremediation of trichlorophenol and phenolic allelochemicals (Shafi et al., 2019). Currently, targeted plant metabolic engineering may be implemented at several levels (Unyayar et al., 2004). By definition, improving a gene's expression or eliminating it can increase a metabolic pathway's efficiency. The combination of pre-existing enzymes allows for further development of the metabolic solution space. Metabolic flux can be steered toward a certain product by reestablishing the metabolic network. As demonstrated by (Reynolds et al., 2005), the utilization of improved photorespiratory pathways in tobacco plants, in conjunction with the blocking of the native pathway, leads to a significant increase in the biomass and photosynthetic efficiency of the plants.

Perspectives and Challenges

Many quantitative loci may control the same agronomic variable, and association and regulation of different agronomic features concerning modularity are frequent occurrences. In the field of potential crop development, resolving adverse compromises among several characteristics—more especially, those linked to crop yield and resilience to biotic or abiotic stresses—remains a tough task. This complexity significantly impedes conventional reproduction (Golfam et al., 2021). As noted before, semidwarf cultivars of the Green Revolution, although very productive, usually require more water and fertilizer with a high nitrogen content. Therefore, to progress the growth of current crops, stress tolerance needs to be improved while maintaining yield efficiency, water, and fertilizer use (Gebeyehu, 2020).

Conclusion

The main goal of crop improvement and crop design for the future is to create future-ready crops with many features. To achieve this goal, a thorough examination of the regulatory networks supporting the hub genes is required for the generation of agronomic traits throughout the entire genome is essential.

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There is no conflict of interest among the authors regarding this case study.

Authors Contribution

All authors contributed equally.