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Current challenges and future perspectives of plant and agricultural biotechnology

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Advances in understanding plant biology, novel genetic resources, genome modification, and omics technologies generate new solutions for food security and novel biomaterials production under changing environmental conditions. New gene and germplasm candidates that are anticipated to lead to improved crop yields and other plant traits under stress have to pass long development phases based on trial and error using large-scale field evaluation. Therefore, quantitative, objective, and automated screening methods combined with decision-making algorithms are likely to have many advantages, enabling rapid screening of the most promising crop lines at an early stage followed by final mandatory field experiments. The combination of novel molecular tools, screening technologies, and economic evaluation should become the main goal of the plant biotechnological revolution in agriculture.

Plant biotechnology and agriculture: targets, plant resources, and scientific tools

The potential contribution of plant and agricultural biotechnologies to solve some of the major issues of world population, food supply, and climatic–environmental changes are discussed elsewhere [1]. This is further emphasized by a recent report [2] clearly revealing that world population is unlikely to stop growing this century, contrary to previous estimations. Production of novel plant-based biomaterials, an additional target for plant agriculture, is discussed here separately.

While agricultural production advanced impressively during past decades due, among other factors, to the implementation of biotechnological tools, several remaining important issues must be addressed. The major current missions of plant and agricultural biotechnology are mentioned below and are further discussed in this opinion article:

- the contribution of new plant biotechnological tools to advanced crop breeding;
- bottlenecks holding back the translation of genomic data to crop plant traits (i.e., the genotype–phenotype gap);
- the crucial importance of plant adaptation and tolerance to abiotic and biotic stress for sustainable agricultural production;
- the role and significance of epigenetics for plant development under changing environmental conditions; and
- plant biomaterials and biofuels as a novel scope of agricultural biotechnology.

The major targets of plant and agricultural biotechnologies, which are illustrated as the processing and screening funnel (Figure 1), include sustainability (practicing agriculture *vis-à-vis* taking care of our environment and keeping a proper ecological balance), food security (i.e., yields – both quantity and quality – supplying caloric needs, proteins, lipids, vitamins, and all other nutritional factors), and the production of novel biomaterials (e.g., plant-based pharmaceuticals, bioplastics, biofuels). The wide reservoir of millennia-old plant and gene resources (at the top of the funnel), emanating from ancient plant evolution and domestication since the first agricultural revolution, were followed by gradual, long-term changes in crop qualitative and quantitative traits through continuous natural and human-directed breeding and selection. It is noteworthy that of a total of approximately 400 000 species of flowering plants, less than 200 have been domesticated as food and feed plants and only 12 species provide 75% of the food eaten [FAOStat (2010) *Production Data Relating to Food and Agriculture* (http://faostat.fao.org) Figure I]. This science-based traditional plant breeding has produced most of the crop varieties that we use today. However, the traditional techniques are no longer sufficiently powerful to satisfy current and future needs for the three targets mentioned above. Understanding of genomics paradigms has advanced considerably in the past decade. This resulted in a more integrative and deeper comprehension of how genetic and epigenetic processes regulate plant growth and development and response to the environment. The era of omics, including genomics, transcriptomics, epigenomics, proteomics, and metabolomics, is poised to facilitate biotechnological improvement of crops, particularly for physiological phenotypes that are controlled by

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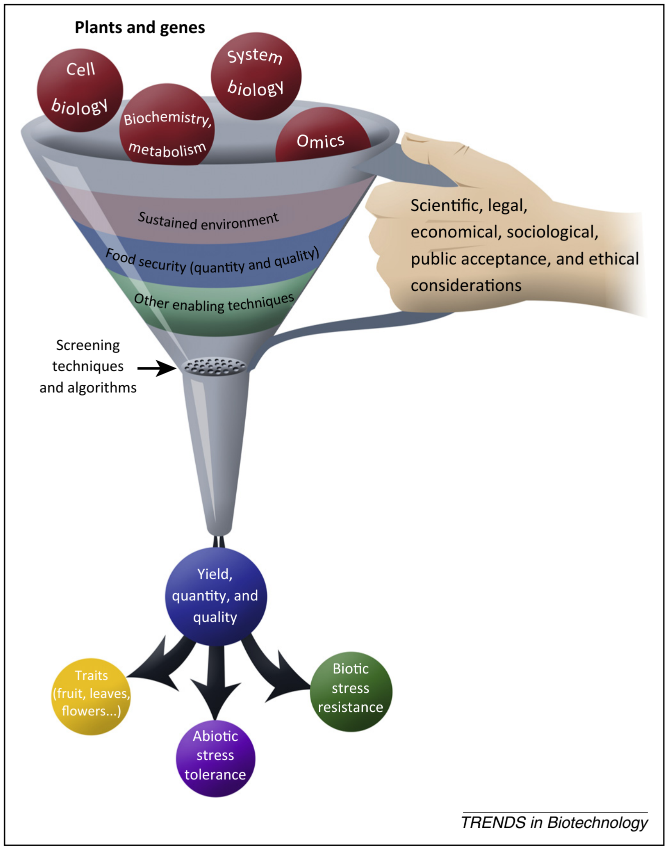

Figure 1. The agricultural biotechnology processing and screening funnel. The agricultural biotechnology landscape is presented here as a processing and screening funnel comprising the major targets of plant and agricultural biotechnologies. The funnel is nourished by the various 'ingredients'; that is, diverse scientific inputs in addition to plants and their genomes. Following appropriate screening techniques, the various agricultural products and traits are expressed and released for consumers. The hand holding the funnel emphasizes that all biotechnological applications should be evaluated with respect to their contribution to global food security and judged by economic, sociological, legal, and ethical criteria.

complex genetic and epigenetic mechanisms. Since many developmental and environmental responses are known to be regulated by epigenetics, it is predicted that reprogramming of the epigenome will be a substantial factor in crop breeding and cultivar development [3]. Abiotic stress might induce epigenetic changes as well, and epigenetic regulators might have an adaptive advantage – although we must consider a negative impact on crop yield by preventing the plant from growing to its full potential [4].

Further advances in plant biotechnology and agriculture depend on the efficient combination and application of diverse scientific inputs (Figure 1) as the ingredients going into the biotechnology processing funnel: cell biology, biochemistry, and metabolism, the various omics, systems and synthetic biology approaches, and other, enabling techniques (e.g., tissue culture, transformation, informatics). Additional major achievements in plant biology are the new methods of plant genome engineering. For example, the bacterial RNA-directed CRISPR–Cas9 endonuclease is a versatile tool for site-specific genome modification in eukaryotes. This method is applicable for genome editing of any model organism and minimizes confounding problems of off-target mutations [5] and is expected to become a method of choice, in addition to other novel technologies, for allelic modifications, gene replacement, structural characterization of the proteome, and post-translational modifications [6]. This rapidly expanding genome engineering toolkit may provide unprecedented control over the genetic information of plant genomes [7] and is important for elucidating plant metabolic, physiological, and morphological traits and therefore for better controlling and modifying biological structure and function [8,9].

Unlike laboratory studies, the realization of plant biotechnologies in the field cannot be translated and applied to agricultural practices without rigorous testing procedures and screening techniques employing reliable algorithms, as depicted by the funnel screen. Multinational research is already taking into account the biology–agriculture crosstalk, paving the way to more effective and productive development of new cultivars (Figure 2).

Once the screening parameters have been satisfied, the products of plant and agricultural biotechnologies are released from the processing and screening funnel into the field and the market (Figure 1). The variety of products and traits include agricultural products for direct human consumption (e.g., grains, fruits, tubers, bulbs, corms, leaves, flowers, fibers, cork, timber). Both product yield and quality (e.g., nutritional value, market and storage ability, taste, color, aroma) and botanical traits of importance to plant development (e.g., shoot and root architecture, growth and elongation, genetic control of flowering) [10–14] must be considered. Most important in view of the detrimental changes in climatic conditions are tolerance and adaptation to abiotic (drought, salinity, extreme temperatures, pollution) and biotic (e.g., fungal and bacterial diseases, insects) stresses. Seed companies are investing enormous effort into developing crops with higher tolerance to drought, heat, cold temperatures, and salinity [15]. Recent studies have identified a large number of genetic and molecular networks underlying plant adaptation to adverse environmental growth conditions [16]. All of these studies emphasize the complexity of the various traits and their polygenic nature (Box 1). Finally, as depicted by the hand holding the funnel, all biotechnological applications should be scrutinized with respect to global food security, economic, sociological, legal, and ethical considerations, aiming at public acceptance [17–21].

Bridging the genotype–phenotype gap

Pre-field phenotyping to increase the proportion and number of high-potential crop candidates, thus saving time and money and bridging the genotype–phenotype gap, is one of the major agrotechnology visions (Figure 2). Gene discovery integrates molecular biology and omics tools and procedures, as depicted in the discovery panel. This is followed by the proof of concept panel, which includes gene transfer stages and various tissue culture operations. Early development of transformed plant candidates occurs following *in vitro* plant regeneration, yielding plant candidates for various traits. The plant candidates that have passed the discovery and proof-of-concept phases undergo several additional evaluation and assessment steps throughout the screening and development phases, selecting the lines

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