Science

Article Type: Perspective

New Plant Breeding Technologies for Global Food Security

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A world without hunger is possible, but only if food production is sustainably increased and distributed, and extreme poverty eliminated. Globally, most of the poor and undernourished people live in rural areas of developing countries where they depend on agriculture as a source of food, income, and employment. International data show a clear association between low agricultural productivity and high rates of undernourishment (1). Global studies have also shown that rapid reduction of extreme poverty is only possible when the incomes of smallholder farmers are increased (2). Therefore, sustained improvement in agricultural productivity is central to socioeconomic development.

In the past, conventional plant breeding has played a major role in improving agricultural productivity. Moreover, the adoption of genetically modified (GM) crops by smallholder farmers has contributed to higher yields, lower pesticide use, poverty reduction, and increased food security (2). Nevertheless, so far only a few developing countries, such as China, India, Pakistan, Bangladesh, and South Africa, have embraced GM crops. Even though three decades of research show that GM crops are not inherently more risky than conventionally bred crops (3), many other countries in Africa and Asia are hesitant to promote the use of GM crops, largely because of

erroneously perceived risks and fears of losing export markets. Many of these fears arose from events occurring early in the application and promotion of GM crops.

In the meantime, new types of breeding technologies have emerged. These new technologies may help to allay some of the fears associated with the more traditional types of GM crops. For example, recent advances in genome editing allow the alteration of crop traits without transferring transgenes across species boundaries. In particular, CRISPR/Cas-mediated genome editing has emerged as one of the foremost systems, with rapidly increasing types of agricultural applications, not only in major cereal crops such as rice, wheat and maize, but also in other food security crops such as cassava and banana (4). The absence of transgenes in genome-edited crops could also lower the costly regulatory procedures associated with GM crops and thus speed up innovation, increase competition in the seed industry, and make improved seeds more affordable for farmers in developing countries (2). The lack of technical, regulatory, and communication capacities to handle GM technologies locally has contributed to limited public acceptance and adoption (5). Scientific and socio-political developments are not always a continuum. Adoption of technologies is seen as the mandate of ‘downstream’ development professionals, which splits ‘research’ and ‘scaling’ and distances research activities from beneficiaries. Therefore, we anticipate that a renewed effort and strategy is necessary to facilitate the use and adoption of new breeding technologies. Learning lessons from the past, the strategy should be based on the three pillars: communication, capacity building and regulation (Figure 1).

Public-private partnership has been perceived by many as one way to promote and implement modern breeding technologies. Such partnership is especially promising in emerging countries that are still home to a large number of poor people but already in a position of economic strength to negotiate mutual benefits with private agribusiness companies. Plant produce and seeds from emerging countries could then also be delivered regionally to neighboring less-developed countries, which would otherwise have limited access to new technologies or would have to pay much higher prices. An existing intergovernmental initiative for rice seeds without borders is a major step in this direction, which allows for seed sharing between a number of South and South-East Asian countries (6).

Such policy initiatives highlight regional efforts and capacity building as a whole, to address poverty, hunger and malnutrition through agriculture in close collaboration with private companies. These initiatives could be taken to a new level through companies working with Asian and African regional development and cooperation bodies such as the Association of the South-East Asian Nations (ASEAN) or the New Partnerships for Africa’s Development (NEPAD). Opportunities exist to capitalize on previous success stories of public-private partnership, such as

the development and commercial release of GM insect-resistant eggplant in Bangladesh. The recent public declaration of the Bangladesh Minister of Agriculture in support of biotech and the initiatives of field-testing three additional GM crops position Bangladesh as a global model for addressing hunger and malnutrition through modern technology (7). Another example is the Water Efficient Maize for Africa (WEMA) project, in which drought-tolerant varieties are being developed with the intention to make these available royalty-free to smallholder farmers through African seed companies (8).

The power of new breeding technologies can best be harnessed for the benefit of the poor when combined with innovative policy initiatives and partnerships. Both public-public and public-private partnerships are key for providing the necessary capacity-building for plant biotechnologists and breeders as well as for policymakers in national and regional institutions (9). Beyond capacity-building, a concerted development plan for priority traits in food crops should be elaborated that would help to rapidly demonstrate the potential of new breeding technologies for food security in developing countries.

Rapid Generation Advance (RGA) and critical selection on elite (but genetically variable) breeding populations (15), and single seed descent strategies are already contributing to improvement of some grains crops, building on the slower and less accurate pedigree selection methodologies that characterized the Green Revolution (16). Along with these, genomic selection, which uses genotyping and imputation as a strategy to predict the value of uncharacterized lines, is also becoming popular (17). Current limitations in breeding methods can also be partially addressed by the recent emergence of the CRISPR/Cas systems that provide an effective suite with various modalities and molecular tools to precisely and efficiently alter the genome in a user-defined manner. CRISPR/Cas9-mediated targeted mutagenesis for functional gene knock-out is widely used for a variety of applications in crop improvement. Other possible modalities include homology directed repair for precise DNA sequence editing, gene replacement and stacking applications, thereby maximizing possibilities for trait improvement. Promoter *cis*-element engineering by CRISPR/Cas9 is also used to alter the transcription patterns for crop improvement (10). Furthermore, CRISPR-base editors can be used to generate specific single-base editing for trait development. CRISPR genome-wide screens could identify novel traits of value. CRISPR/Cas technologies can expand the range of traits and accelerate trait development in diverse crop species. However, the utility of CRISPR technologies to improve quantitative traits including drought and salt tolerance remains to be tested in several crop species. We anticipate that CRISPR/Cas technologies, in combination with modern breeding methods, will play an important role in future crop improvement programs, but other technologies for genomic prediction and

selection will, of course, also remain very important.

Several interesting applications of genome editing may already become available in the short and medium run. For instance, multiple food security crops could immediately benefit from the new genome-editing technologies to solve major pest and disease problems and make plants more resilient to climate stress (Supplementary Table 1). Successful public or public-private development of related crop varieties could serve as a clear example to build trust and demonstrate local capacities to use genome editing for local benefits. The target genes for improvement are now more easily identified by the increasing number of high-quality crop genomes and the allelic comparisons in crop/plant diversity panels. Availability of such diversity in public databases is being recognized by the private sector, which could foster mutually beneficial public-private partnerships. The publicly-funded Consultative Group on International Agricultural Research (CGIAR) has a mandate for most of the major food security crops and unites regional organizations engaged in research for a food-secure future (11). Most CGIAR centers support crop-specific genebanks whose accessions could be assessed for genome-edited improvements, in collaboration with regional and national institutes. Previous efforts of the CGIAR to provide germplasm to developing countries made it easier for breeders to develop new crop varieties. Given their presence in different local environments, the CGIAR centers could be a neutral coordinator of a network of field research facilities for development and testing of genome-edited crops.

Global opposition to GM crops accounts for the fact that only very few concrete applications of these crops have materialized until now. European attitudes and policy approaches are very important in this respect. Given their longstanding trade connections to Europe, African and Asian nations also logically fear that adoption of GM crops could lead to the loss of export opportunities to Europe where opposition to GMOs is now deeply ingrained (12). As mentioned, genome editing could represent a renewed opportunity to harness the potentials of modern biotechnology for food security. However, the recent EU Court ruling to regulate genome-edited crops in the same way as GM crops (13) is disappointing and could seriously stifle international progress. Nevertheless, the rulings by the United States (14) and Japan on relaxation of rules towards genome-edited crops are expected to set the ground for a new paradigm that could lead to more efficient regulation internationally. Over 30 years of experience with GM crops show that regulatory procedures influence public attitudes, and that negative public attitudes in Europe can have a significant effect on public and policy perceptions in developing countries (2). A less restrictive regulation of genome-edited varieties in the EU could therefore send a positive signal to developing countries in need of agricultural technologies for food security.

In conclusion, future success towards global food security will require a framework based on the

lessons learnt from the past – innovation is essential, and thus an environment facilitating innovation is essential. In order to fully exploit the potentials of new breeding technologies, a multipronged approach is needed, taking into consideration all components involved in technology development, dissemination, adoption, and social acceptance (Figure 1). New breeding technologies should not be misunderstood as a panacea. Many other technologies and approaches are needed as well, including improvements in post-harvest management, market infrastructure, and social services. However, genome-editing is predicted to be a powerful addition in the fight against hunger and poverty. The global community should seize this opportunity by developing conducive regulatory frameworks.

Figure 1: Key factors in the rationalized delivery and social adoption of New Plant Breeding Technologies (NPBTs) for global food security.

Supplementary Material

Supplementary Table 1: Grand regional/global challenges where new plant breeding technologies can provide immediate solutions

References

1. FAO, *State of Food Security and Nutrition in the World* (FAO, Rome, 2018)..1.
UNDP-India, Available online at

- 157 [http://www.in.undp.org/content/india/en/home/sustainable-](http://www.in.undp.org/content/india/en/home/sustainable-development/successstories/MultiDimesnionalPovertyIndex.html)
 158 [development/successstories/MultiDimesnionalPovertyIndex.html](http://www.in.undp.org/content/india/en/home/sustainable-development/successstories/MultiDimesnionalPovertyIndex.html) (2018).
- 159 2. M. Qaim, *Genetically Modified Crops and Agricultural Development*. (Palgrave
 160 Macmillan, New York, 2016).
- 161 3. A. Nicolia, *et al.*, *Crit Rev Biotechnol* **34**, 77-88 (2014).
- 162 4. S. E. Bull, *et al.*, *Sci Adv* **4**, eaat6086 (2018).
- 163 5. O. C. Ezezika, *et al.*, *Nat Biotechnol* **30**, 38-40 (2012).
- 164 6. IRRI, Available online at [http://irri.org/news/media-releases/agreement-on-multi-](http://irri.org/news/media-releases/agreement-on-multi-country-seed-sharing-reached)
 165 [country-seed-sharing-reached](http://irri.org/news/media-releases/agreement-on-multi-country-seed-sharing-reached) (2018).
- 166 7. IRRI, Available online at [http://oneworld.org/2018/2003/2007/bangladesh-agriculture-](http://oneworld.org/2018/2003/2007/bangladesh-agriculture-minister-backs-golden-rice-and-gm-crops)
 167 [minister-backs-golden-rice-and-gm-crops](http://oneworld.org/2018/2003/2007/bangladesh-agriculture-minister-backs-golden-rice-and-gm-crops) (2018).
- 168 8. S. Oikeh, *et al.*, *Convergence of Food Security, Energy Security and Sustainable*
 169 *Agriculture*, 317-329 (2014).
- 170 9. H. Vanderschuren, *Nat Biotechnol* **30**, 1170-1172 (2012).
- 171 10. S. Svitashhev, *et al.*, *Plant Physiol* **169**, 931-945 (2015).
- 172 11. M. Renkow, *et al.*, *Food Policy* **35**, 391-402 (2010).
- 173 12. S. J. Smyth, *et al.*, *Plant Biotechnol J* **11**, 527-534 (2013).
- 174 13. EUCJ, [https://curia.europa.eu/jcms/upload/docs/application/pdf/2018-](https://curia.europa.eu/jcms/upload/docs/application/pdf/2018-2007/cp180111en.pdf)
 175 [2007/cp180111en.pdf](https://curia.europa.eu/jcms/upload/docs/application/pdf/2018-2007/cp180111en.pdf) (2018).
- 176 14. E. Waltz, *Nat Biotechnol* **36**, 6-7 (2018).
- 177 15. G. N. Atlin, *et al.*, *Glob Food Sec* **12**, 31-37 (2017).
- 178 16. A. Watson, *et al.*, *Nat Plants* **4**, 23-29 (2018).
- 179 17. J. M. Hickey, *et al.*, *Nat Genet* **49**, 1297-1303 (2017).

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Supplementary Table 1: Grand regional/global challenges where new plant breeding technologies can provide immediate solutions

Food crop	Target region / community	Food security issue	Yield losses	How New Breeding Technologies (NBTs) can help
Wheat	West Asia, North Africa	Powdery mildew	Up to 40% on average, 100% in case of early infection	<ul style="list-style-type: none"> Genome editing of <i>MLO</i> (1) (encoding a membrane-associated protein that inhibits fungal penetration of host) or/and <i>MPK3</i> (2) (encoding a Raf-like mitogen-activated protein kinase kinase kinase (MAPKKK)) in stably transformed local cultivars Speed breeding for rapid introgression of <i>TaEDR1</i> resistance alleles (3) into local cultivars
Maize	South and East Africa	Drought		<ul style="list-style-type: none"> Genome editing of a gene encoding a transcription factor regulator of ethylene responses <i>AtERF1</i> (4) in stably transformed local cultivars
Rice	South-East Asia	Rice blast (<i>Magnaporthe oryzae</i>)	10-30% loss in annual production	<ul style="list-style-type: none"> Genome editing of an ethylene response gene <i>OsERF922</i> (5) in stably transformed local cultivars
		Bacterial leaf blight (<i>Xanthomonas oryzae</i>)	Up to 70% under favorable conditions	<ul style="list-style-type: none"> Genome editing of a sucrose transporter gene <i>OsSWEET14</i> (6) in stably transformed local cultivars
		Drought	Up to 30% loss in rainfed production zones	<ul style="list-style-type: none"> Genome editing of genes in the <i>qDTY12.1</i> (7) especially the gene <i>OsDRO1</i> (8) recently characterized as a drought tolerance gene in the rice architecture (IRRI, unpublished results)
Cassava	East and Central Africa	Cassava brown streak disease	Annual losses worth US\$1billion	<ul style="list-style-type: none"> Genome editing of elongation factor <i>EF1A</i> (9) in stably transformed local cultivars
Banana	West and Central Africa	<i>Fusarium</i> wilt	40-60%, responsible for Panama disease epidemic	<ul style="list-style-type: none"> Replacement of <i>RGA2</i>, a nucleotide-binding domain leucine-rich repeat (NB-LRR)-type receptor (10) with a resistant allele (11) using CRISPR/Cas RNP in banana

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222 **References**

- 223 1. Y. Wang, *et al.*, *Nat Biotechnol* **32**, 947-951 (2014).
224 2. Y. Zhang, *et al.*, *Plant J* **91**, 714-724 (2017).
225 3. A. Watson, *et al.*, *Nat Plants* **4**, 23-29 (2018).
226 4. J. Shi, *et al.*, *Plant Biotechnol J* **15**, 207-216 (2017).
227 5. F. Wang, *et al.*, *PLoS One* **11**, e0154027 (2016).
228 6. S. Blanvillain-Baufume, *et al.*, *Plant Biotechnol J* **15**, 306-317 (2017).
229 7. S. Dixit, *et al.*, *Sci Rep* **5**, 15183 (2015).
230 8. M. A. Gomez, *et al.*, *Plant Biotechnol J*, (2018).
231 9. J. Dale, *et al.*, *Nat Commun* **8**, 1496 (2017).

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234