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EDITORIAL

Plant breeding for increased sustainability: challenges, opportunities and progress

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Humanity is facing enormous challenges in the years to come: sustainability of agriculture and sustainability of our supply with food, feed and renewable materials are neither granted nor free. Especially, but not only, in the Global South, a sustainable increase in agricultural productivity and a steady reduction of avoidable losses are undoubtedly key issues that need to be addressed.

In order to pinpoint the most pressing challenges and strategies to achieve targets, the United Nations have formulated the Sustainable Development Goals (https://sdgs.un.org/goals). Among these, several are directly or indirectly addressing agriculture, food supply and sustainability, most notably SDG2 (zero hunger), SDG12 (responsible consumption and production), SDG13 (climate action) and SDG15 (life on land).

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Crop productivity: stable yields for sustainable production

While the productivity for some crops has increased steadily, such as the wheat yields in India and Pakistan, from less than 1 t ha^{-1} in the 1960s to around or above 3 t ha^{-1}in recent years (Fig. 1C, data from FAOSTAT: www.fao.org/faostat) as fueled in part by agricultural improvements associated with the Green Revolution (Pingali 2012), other crops and other regions have been lagging behind or stagnating. As an example, average chickpea yields in Pakistan have not increased since the 1960s and in India have increased only moderately from 0.6 t ha^{-1} to about 1 t ha^{-1} now (Fig. 1E). Maize yields in many African countries have steadily increased, but reached an absolute yield plateau, which is much below the yields in Europe, for instance. As an example, average maize and sorghum yields in Kenya, Burkina Faso and Nigeria typically fluctuate between 1.5 and 2 t ha^{-1} and 0.6 to 1.4 t ha^{-1}, respectively (Fig. 1D, F), whereas average maize yields in France and Germany are approximately 5 times higher, ranging between 8 and 11 t ha^{-1} (Fig. 1B).

Numerous factors and challenges are still hampering progress in agriculture in the Global South, such as Sub-Saharan Africa, due particularly to a chronical lack of investment in rural and agricultural development, and limited access to improved technology and inputs. The latter includes insufficiency of long-term investment in breeding improved crop cultivars adapted to local conditions and lack of genotype by environment by management packages that also acknowledge the social context (Wilkus et al. 2021). Crop yields in many industrialized countries have increased steadily during the past few decades, reaching high levels. As an example, average yields for wheat and maize in Western Europe (France and Germany) increased in an almost linear manner until the early 1990s, but reached a plateau at around 8 to 11 t ha^{-1} for maize and 6 to 8 t ha^{-1} for wheat since the early 2000s (Fig. 1A, B). High-input crop production has raised

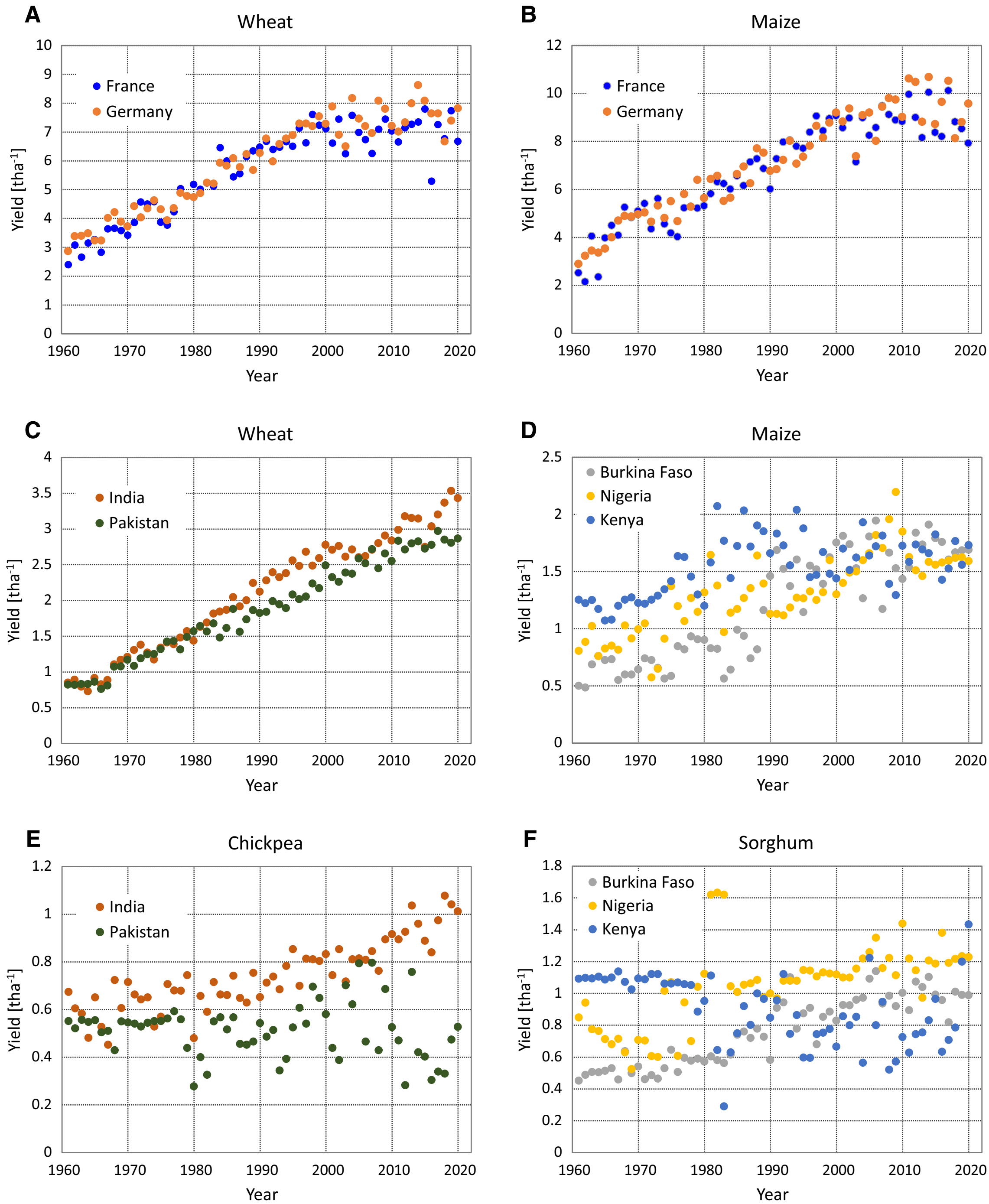

Fig. 1 Yield of selected crops in selected countries from 1961 to 2020. **A** Wheat in France and Germany, **B** Maize in France and Germany, **C** Wheat in India and Pakistan, **D** Maize in Burkina Faso, Nigeria and Kenya, **E** Chickpea in India and Pakistan, **F** Sorghum in Burkina Faso, Nigeria and Kenya. Yield data in t ha^{-1} retrieved from FAOSTAT: www.fao.org/faostat

yields significantly but at the same time led to problematical side effects due to high amounts of mineral fertilizer or manure applied, reliance on a small number of large acreage crops, and risks associated with chemical crop protection. To mitigate these negative effects, many European countries implemented farmer incentives to reduce external input and propagate eco-friendlier agriculture. The European Union has coined its strategy on agriculture and food in the European "Green Deal—From Farm to Fork" strategy, which aims to accelerate a transition to a more sustainable food system, demanding significant reductions in agrochemical and fertilizer use, increasing the area under organic farming and protecting biodiversity (https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en).

Plant breeding: crop improvement for sustainable production

Plant breeding is certainly a key sector that has contributed to enhancing sustainable crop production in the past and will likely play an even bigger role in the future. As an example: wheat yields at the farm gate in Germany have risen by 89 kg ha^{-1} y^{-1} since 1961. Since the year 2000, however, annual increases slowed down to an average of 18 kg ha^{-1} y^{-1} (data from FAOSTAT). One may ask the question: "What is the contribution of genetic improvement to these productivity gains?" The publication by Voss-Fels et al. (2019) offers an answer: they compared winter wheat cultivars released in Germany from 1965 to 2013 for numerous traits, including grain yield, in well-replicated experiments. Based on their data, the average grain yield increase of wheat cultivars was found to be 32 to 42 kg ha^{-1} y^{-1} of release depending on the intensity of the production system. The study also revealed that the annual yield increases due to improved cultivars had a steady upward trend across the entire period and did not show signs of stagnation in the later period of cultivars released between 2000 and 2013. This indicates that even after more than 100 years of breeding, the genetic potential of wheat yield has not been exhausted and this is clearly evident under both high-input and low-input farming. For industrialized countries, this example implies that particularly under reduced external input cropping systems, improved cultivars will likely continue to be an avenue to maintaining yield and quality of our crops. At the same time, the projection of breeding to enhance sustainable crop production is even more inspiring for the developing countries, where we expect that the contribution of crop improvement to better crop sustainability is at least as important, or even more so than in the developed world, which should go hand-in-hand with improvements in agronomic practices.

Challenges, opportunities and progress

In this Special Issue, we cover a range of aspects of crop improvement with a clear link to long-term sustainability. Several papers address the ever-important topic of resistance to pests and diseases. Deployment of resistant cultivars is the cornerstone of integrated crop protection and will gain in importance in the years to come. Precisely targeted breeding for resistance to septoria nodorum blotch in wheat has become a reality since this plant-pathogen complex has been largely uncovered and understood. The wheat *Parastagonospora nodorum* pathosystem mostly follows an inverse gene-for-gene model. Knowing the fungal effectors and the host's sensitivity genes can now be exploited for resistance improvement (Peters Haugrud et al. 2022). Resistance to crown rust in oat is a key trait necessary to keep this relatively small crop attractive for farmers, thus contributing to maintaining diversity in agriculture. Crown rust in oat is no exception as high diversity in the pathogen populations has been found, followed, fortunately by a concurrent sufficient diversity in major and minor resistance genes in the hosts gene pool exploitable for breeding (Park et al. 2022). In addition, pest and disease resistance in faba bean is covered (Rubiales and Khazaei 2022) as well as resistance to downy mildew in sunflower (Molinero-Ruiz 2022). An extremely informative resource for soybean resistance improvement has been compiled by Lin et al. (2022) providing well-structured information on more than 800 loci/alleles associated with disease resistance and their tightly linked markers for 28 soybean diseases, caused by nematodes, oomycetes, fungi, bacteria, or viruses.

Breeding for pest resistance is in most instances more resource demanding and more challenging than fungal or viral disease resistance, but will require more investment in the years to come (Wani et al. 2022). Since the fall armyworm has invaded Africa, Asia and Australia, it became a serious threat to maize cultivation in these regions and thus to food security. Knowledge and strategies to combat this devastating pest are discussed in Prasanna et al. (2022). A significant contribution of increased pest resistance to integrated crop production is a must-have for future canola cultivation, and new ideas and approaches toward this goal have been presented by Obermeier et al. (2022). Current cultivation of perennial crops such as fruit trees and grapevine relies heavily on chemical pest and disease control, and both breeding and adoption of new cultivars are typically slow. New ways and new tools to accelerate cultivar resistance for grapevine (Topfer and Trapp 2022) and perennial fruit trees (Khan and Korban 2022) are therefore urgently needed.

Whereas mechanisms and occurrences of epigenetic variation have been intensively studied in recent years in model plants (Schmitz and Ecker 2012), the possible role of epigenetic variation in crop breeding is still largely unexplored, which is discussed by Varotto et al. (2022).

Organic crop production is an agricultural system gathering evidence regarding its sustainability at different scales, and an increased demand of organically produced crops is evident; both factors are incentives to invest into developing cultivars for organic farming. Crop improvement explicitly targeting sustainable agriculture practices for selection with farm to table participatory perspectives are critical to achieving long-term sustainable crop production, for which an example is outlined by Sandro et al. (2022), who describe a scenario for organic winter wheat breeding.

Opportunities for combining superior productivity with low susceptibility to lodging through utilization of alleles already present in elite material are covered by Dreccer et al. (2022). Rebetzke et al. (2022), who explored seminal root length, root number and grain yield under drought stress in a wheat mapping population, present a novel and promising approach to breed future wheat cultivars with improved resistance to drought stress, a breeding target that will gain significance globally. Crops underwent genetic bottlenecks, and it is well known that rich diversity has been left behind so far in crop plant relatives. In order to unlock diversity for grain quality traits including micronutrient concentrations, Zeibig et al. (2021) report on results in wheat and wheat relatives for these traits, which should allow more targeted allele mining. Unlocking 'neglected or underutilized' diversity for future crop improvement is likewise addressed by Badaeva et al. (2022) who provide an extensive study on the tetraploid wheat section *Timopheevii* and its potential for wheat improvement.

Crop modeling and better understanding of the phenomenon of genotype by environment interactions have the potential to contribute to breeding better adapted cultivars, as the example on sunflower (Casadebaig et al. 2022) illustrates. Rice is the staple food for a whole continent and sustainability of rice cultivation is indispensable. The meta-analysis of genomic regions involved in heat and drought stress of rice by Kumar et al. (2022) sheds light in the genetic makeup of this trait and thus opens avenues for improvement. The global demand for high-quality plant-based protein increases steadily. Soybean, with its unique composition of high-quality protein and oil, is the most widely grown legume globally. Maintaining and understanding diversity in this crop for agronomically important traits such as plant height (Bhat et al. 2022) and for root development and growth under low-nitrogen environments (Wang et al. 2022) will contribute to sustainability of soybean cultivation. Likewise, the article by Guo et al. (2022) contributes to a better understanding and targeted unlocking of genetic diversity in cultivated and wild soybean with an emphasis in seed protein content and yield.

Among the macro-nutrients of our crops, phosphorus (P) is the one where global supply is truly limited. Understanding the mechanisms of plants involved in P uptake and P utilization efficiency is necessary to equip future cultivars that can cope with lower P fertilization than currently applied (Ojeda-Rivera et al. 2022).

All in all, it was an inspiring endeavor to shape this Special Issue "Breeding towards Agricultural Sustainability" and we hope it provides insights and ideas to the readers on how to address issues and challenges of sustainable agriculture from a crop improvement standpoint and to capitalize on plant breeding as means to accomplish such goals.

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