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REVIEW

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Plant breeding for organic agriculture: something new?

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Abstract

The role of both organic (OF) and conventional (CF) farming remains open to debate particularly when related to food security and climate change. Targeting plant breeding for OF can contribute to reduce its yield gaps vis-à-vis CF. Currently, the cultivars produced for CF are also used in OF, however, it is unreasonable that all lines bred for CF will always perform well in OF. Nonetheless, plant breeding goals for OF and CF converge at aiming for high productivity, host plant resistance or tolerance to biotic and abiotic factors, and high resource-use efficiency. Likewise end-use quality and local adaptation may be more important for OF as the resource recycling and quality of the inputs that are used vary from region to region, even though OF practices are highly regulated. This article provides an overview on organic plant breeding (OPB) with a perspective from conventional plant breeding, highlights the main traits, their source of variation, and what methods and tools are available for their breeding. It concludes listing some organic crop breeding achievements and providing an outlook on what needs to be done for OPB.

Keywords: Conventional agriculture, Conventional breeding, Organic agriculture, Organic plant breeding

Background

Food supply is a major concern for human kind and takes place in a complex global scenario. On one side there is an increasing demand for food, i.e., the human population, projected to be by 9 billion in 2050 and its dietary shifts, requires more food to be produced, and at the same time humankind is undergoing through an increase of certain medical conditions (type II diabetes, coronary heart disease, etc.) that reduce life expectancy [1]. On the other side, there are factors that seriously threat food production, i.e., climate change and the constant pressure of pests and pathogens, of which the global patterns of infestation/infection are also expected to vary due to this changing climate.

There is much debate on how exactly food must be produced. Even though, there is a general agreement in that sustainable agriculture is to what agricultural systems should aim. However, sustainability has been conceptualized in several ways [2]. From its Latin root (*sustinere*), sustainable means "to maintain," "to support," or "to endure." Sustainability, in the ecological context, is the conservation of the ecological balance by avoiding the depletion of natural resources [3]. The American Public Health Association (APHA) defines sustainable food systems as the ones "that provide healthy food to meet current food needs while maintaining healthy ecosystems that can also provide food for generations to come with minimal negative impacts to the environment" [4]. This food system should also promote local production and make "nutritious food available, accessible and affordable to all" individuals [4].

Organic and conventional farming (CF) systems are the center of a heated debate; particularly, when highly relevant topics, such as food security and climate change, are discussed. Especially, when supporters of organic farming (OF) claim that this system is synonymous of agricultural sustainability or imply in their argumentation that OF is the only way to achieve sustainable food production [5] and that it could also secure global food supply [6, 7]. These arguments have been thoroughly analyzed by other authors [8–10], and the conceptual differences between sustainable agriculture and OF have already been pointed out [2].

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It is important to note here that low-input farming systems, which are driven by resource-limited farmers, are considered within CF. This implies that the so called "breeding for CF" also encompasses those low-input/tech cropping systems. We consider that this inclusion is relevant since OF enthusiasts usually consider CF only as a high-input system, and also because of the plant breeding purposes of obtaining widely adapted cultivars.

Organic farming, food supply, and the environment

The aim of OF is the creation of holistic farming systems that are sustainable in all regards. This approach should therefore rely on the use of farm-derived renewable resources that provide acceptable levels of crop, livestock, and human nutrition. OF should also provide protection from pests and pathogens due to the harmonious management of resources and understanding of ecological and biological processes. The very well-known characteristic of OF is that it produces food without the use of any synthetic fertilizer or pesticide, and neither with the use of genetically modified organisms (GMO). For this reason OF enthusiasts consider these systems to have positive impacts on the environment by enhancing soil fertility, contributing to mitigate climate change, and conserving biodiversity.

Research has shown that OF can contribute to reduce soil carbon losses, mainly due to the application of organic fertilizers such as compost or stacked manure which should derive from the integration of crop production and livestock. Research comparing the dynamics of soil organic carbon between OF and CF shows that the former can significantly increase the concentration, stock, and sequestration rates of organic carbon in the soil [11]. Still, this feature alone of OF is not able to mitigate climate change, because it does not tackle the issue of reducing the emission of greenhouse gases (GHG), and neither accounts for N_2O or other emissions derived from agricultural practices [11].

GHG emissions in OF vary depending on the agricultural product. For example, organic beef and some organic crops emit less GHG compared with their counterparts in conventional systems, whereas the organic production of milk, pork, poultry, and egg emit between 16 and 46 % more GHG because of their higher methane and N_2O emissions [12, 13].

High concentrations (7 %) of organic matter in the soil are another feature of OF [12]. The evidence shows that this is not due to the higher inputs (65 %) of organic fertilizers per se in OF than in CF, but rather due to a cascade effect in which an increased microorganism activity decomposes the organic residues [12]. But, tillage and crop rotation may play a role in increasing the organic matter content in the soils. In CF also it is possible to increase the concentration of organic matter in the soils by increasing manure inputs [12].

Biodiversity in OF is generally reported to be between 10.5 and 30 % higher than in CF [14–16]. However, when Gabriel et al. [16] studied the biodiversity in winter cereals in UK by contrasting both farming systems, they concluded that this increase in biodiversity is highly correlated with grain yield reductions independently of the production system. This finding means that CF can be as diverse as OF with lower yields, and thus OF "*per se* does not have an effect (on biodiversity) other than via reducing yields and therefore increasing biodiversity." Hence, "in high-productivity landscapes, OF is not an efficient way of maximizing diversity and yield, but land sparing might be" [16].

The positive impacts of OF on the environment are reduced when looking at the yield gap between this production system and CF. While OF has positive environmental effects when its impact is measured per area unit, it has negative environmental effects in a product unit basis [12]. This is because for OF to reach production levels similar to those of CF there would be a need to increase the agricultural land by 84 % [12], and in the current situation humankind cannot afford to increase the land area where food is produced.

Edible yields in OF are generally lower than in CF. However, the differences highly depend on the agricultural system [9]. For example, the yield difference in fruit and oilseed crops is 3 and 11 % lower than in CF, respectively; while organic cereals and vegetables have a 26 and 33 % of yield reduction in OF [9]. The grain yield gap between OF and CF winter wheat systems is 54 % in the United Kingdom [16], while in Sweden and Finland the edible yield of cereals and potatoes is about 46 and 60 % lower, respectively [17]. Seufert et al. [9] also made a comparison of yield gaps between developing and developed countries and found that the differences are by 43 and 20 % lower yields in OF, respectively. Kirchmann et al. [17] suggest that the main limitation for OF to have high yields is the availability of soil nutrients, weed control, and limited possibility to increase fertility in low-nutrient soils. Other research reported that both farming systems can have similar yields [18, 19]. However, to reach this level of productivity, the nutrient inputs in the form of manure need to be as high or higher than in CF systems, which in great measure originate from conventional systems [17].

Organic farming supporters frequently raise the issue that modern cultivars and particularly transgenic crops fail in contributing to sustainable food production systems due to the strong selection pressure on pests and pathogens caused by those modern resistant cultivars, since eventually such host plant resistance is broken causing new outbreaks of pests and pathogens [20]. However, this is a characteristic of any host plant resistance that puts strong selection pressure on the pathogens and pests [21, 22]. Since in great measure, resistance depends on the type of pathogen that the plants deal with, the evolutionary potential of the pathogen population, and the type of resistance that is being utilized [21, 22]. Yet, it has been shown in wheat that it is possible to breed for broad and durable resistance [23–25].

Conventional farming could certainly become more sustainable by adopting practices that have less negative impacts on the environment [9], and in that sense there is a great potential to improve CF systems. Furthermore, a question that would naturally rise is whether OF is really a sustainable food production system according to the APHA definition, since productivity and affordability are generally not considered in the definition of OF. Thus in agreement with other authors [8–10], we consider that OF today is not the way to sustainably feed the world, particularly in a scenario where food demand is constantly increasing, for which it requires high food productivity with extreme care of the natural resources. However, addressing demand-side factors through policies can greatly contribute to feed the world and preserve the environment [26]. From the food supply perspective we think that sustainable cropping systems can be achieved, by adopting practices that are less harmful to the environment, e.g., deploying resistant or tolerant cultivars to biotic and abiotic stresses along with the improvement of the resource-use efficiency through breeding efforts to reduce the inputs that are harmful to the environment, accompanied with better agronomic practices and technologies that also enhance productivity and resource-use efficiency.

OF may be successful for a niche market in certain developed countries in Europe and the USA, while helping to enrich the organic C content in soil. That said, the higher productivity of integrated farming (OF and CF) is essential for enabling food security in most developing countries.

Organic plant breeding

Targeting plant breeding for OF can contribute to reduce the yield gaps between both production systems: CF and OF. However, the issues of whether these systems should necessarily be regarded as competing entities between each other and if they should necessarily be comparable in terms of productivity require further analysis. Since it is not clear whether OF yields should aim to be equal to those in CF or simply being higher than they are today.

For both conditions, the breeding goals converge at aiming for higher productivity, incorporation of resistance or tolerance to biotic and abiotic factors, and higher resource-use efficiency (water, nutrients, light, etc.). Local adaptation may be more important for OF as the resource recycling and quality of the inputs that are used can vary from region to region, even though OF practices are highly regulated. Likewise, organic plant breeding (OPB) aims to fit cultivars into farming systems relying on renewable organic resources.

One frequent issue noted by OF enthusiasts is that the cultivars bred for CF do not always perform well under OF conditions [27, 28]. There is no reason, however, to think that all cultivars produced by conventional breeding programs will perform well in all environments, even in all CF environments. Consequently, it is unreasonable to think that all lines produced in an organic breeding program will perform well in all OF conditions. The genotype-by-environment interaction (G × E) is a common situation that plant breeders have to deal with and if exploited correctly it is still possible to make important progress in crop improvement. Even under CF, which for some OF supporters it simply consists of high-input-standardized practices, G × E is a highly important aspect to be considered, because in reality there are also low-input and diverse CF systems, driven by the resource-poor farmers in developing countries. Hence, from the pure plant breeding perspective, OF can be considered as a separate environment with a strong component of local adaptation, in which the necessary traits and selection methods should be incorporated.

Traits and sources of variation

Despite that the general breeding goals for both, OF and CF are similar, there are specific traits that are required for OF as the utilization of synthetic agrochemicals are banned in this system. Weed competitiveness and the ability to establish symbiont relations with micro-organisms in the soil are relevant for OF because they can enhance the uptake of resources and its use efficiency [27, 29]. Research has shown that there exists genetic variation for weed competitiveness in cereals [30–33], and that early vigor and allelopathy can be useful traits to enhance weed suppression [30, 34].

Genetic variation for nitrogen use efficiency has been found in potato [35, 36] or wheat [37], and genomic regions associated with this trait have been identified in barley [38]. Additionally, studies have shown that nitrogen use efficiency can be improved through agronomic practices [39]. Genetic variation and genomic regions associated with the uptake of micronutrients have also been reported in wheat [40, 41]. Nelson et al. [42] found, however, that the percent of arbuscular mycorrhizal fungi was negatively correlated with iron and zinc concentrations in winter wheat, but positively correlated with manganese, copper, and potassium. Mycorrhizal fungi play an important role in soil fertility and nutrient uptake in OF systems, whereas in CF their presence is severely reduced [43]. Efforts to breed crops for high micronutrient uptake are undergoing in public plant breeding programs [44, 45], thus OPB can utilize the developed germplasm in such plant breeding programs.

Traits such as tolerance to abiotic stresses (heat, drought, salinity, water lodging, etc.) and host plant resistance to pathogens and pests are not exclusive for OF, but they are highly dependent of the geographical area where the breeding is targeted. Resistance to seed-borne pathogens is of great importance, since seed treatments are limited in organic seed production. Root diseases are considered to be important only during the conversion period from CF to OF [46, 47]. In wheat, for diseases such as rust and powdery mildew, OPB can take advantage of the achievements that have been made in breeding for durable and broad resistance to these diseases [23, 25, 48].

Several authors have described in a more detailed way the necessary traits and ideotypes of cereals and vegetables for OF [27, 29, 49, 50]. Here our aim is not to repeat those descriptions but to emphasize that in our view plant breeding for OF and CF only differs in certain specific traits that are important for the adaptation in either of the environments, but not in the general breeding goals. OPB requires the application of breeding methods that are therefore in line with the OF principles.

The sources of variation to incorporate relevant traits in cultivars for OF conditions are not different from the sources of variation for cultivars aimed for CF; that is in their natural origin. For instance, wild relatives and landraces are sources of variation for both plant breeding systems. The processes of how these sources of genetic variation are incorporated in the production of new cultivars are, however, regulated and subject to OF and OPB principles [27].

In the particular case of wheat, Lammerts van Bueren et al. [27] foresee the utilization of synthetic hexaploids in OPB programs, as they are a rich source of genetic variation for the development of new wheat cultivars [51]. It is not clear, however, whether they can be used for organic wheat breeding, as they are produced with the aid of colchicine treatments [52] which operate below the cell level, and according to some reports they should be forbidden in OF [29, 53, 54].

Methods and tools

Organic plant breeding is restricted to specific conventional breeding practices, in general to crossing methods that do not break the reproductive barriers between species, and to selection methods based on the evaluation and selection of whole plant performance [29, 53, 54]; i.e., (1) intraspecific crossing, (2) backcrossing, (3) mass and individual selection, (4) selection via DNA markers, (5) hybrid cultivars—as long as next generation is fertile and the hybrid production does not chemically induce sterility, and (6) meristem culture. On the other hand, the technologies or methods that engineer plants at the DNA level are considered to be incompatible with OPB [29, 53–55], e.g., (1) genetically modified organisms and (2) the application of synthetic hormones and colchicine treatments.

New breeding techniques make it possible to precisely incorporate particular characteristics from wild crop relatives or landraces into modern crops. In that line, some authors have analyzed the possibility of implementing modern technologies in OPB to rewilding modern crop cultivars [56] and whether this modern techniques can fit within the four principles of OF (health, ecology, fairness, and care). However, Lammerts van Veuren et al. [57, 58], had already argued that cisgenesis and reverse breeding based germplasm are products of processes that corresponds to the development of GMO and thus this technique should be banned from OF and OPB.

Development of cultivars adapted to OF conditions can be successfully achieved if plant breeding programs combine the selection of the progeny in optimal and organic or low-input environments. This can be seen as one of the elements under which the Green Revolution took place [59]: shuttle breeding, which consists in exchanging segregating generations between different environments to achieve wide adaptation or broad disease resistance. Alternation of germplasm between CF and OF at later segregating generations is considered an important component of commercially sustainable OPB programs by some authors [60–62]. A modality of this shuttle breeding scheme, is to only carry out selections of advanced generation progenies, developed by conventional breeding procedures, under optimum organic environments to determine their value for cultivation and use in further testing; this is advantageous, particularly when there is limitation of financial, human, and institutional resources in OPB.

Some authors consider, however, that it is necessary to carry out selection solely under organic environments as it is the only way for the plants to fully express their genetic potential [28, 63]. Thus, participatory plant breeding (PPB) and evolutionary breeding (EB), have been proposed as suitable breeding methods to target OF [64–68]. These methods facilitate the selection for local adaptation and for the particular needs of farmers, they also empower farmers as they allow closer interaction between them and breeders and give farmers greater freedom to choose germplasm. Particularly, for the case of PPB that can lead to a faster cultivar adoption [20, 69].

Conclusion

Organic crop breeding achievements

Private breeding companies (especially small–medium enterprises) and some public institutions, particularly in Europe and North America have finely established OPB programs. For instance in Austria, Canada, France, Germany, Switzerland, and USA organic winter wheat breeding programs have been initiated [27, 70]. Projects in PPB for OF have also been established in tomato [71, 72], cauliflowers [73], and *Lolium* [74], while there are other OPB undertakings for cabbage, broccoli [27], and onion [75] in The Netherlands or spinach in France [76].

Outlook: what is new and what needs to be done for OPB

OPB has certainly made steps forward toward the development of cultivars adapted to OF, particularly after finding that conventional plant breeding cannot always provide suitable cultivars for OF in various crops such as cereals and pulses [77–79]. Below we list some points that may contribute to the further development of cultivars for OF conditions.

- Broad multi-location testing to better exploit G × E and thus identify key locations within regions to conduct cultivar yield trials [80, 81].
- Examine the implementation of shuttle breeding between OF and CF to open the possibility of developing cultivars adapted to both conditions.
- Larger screening of plant materials deposited in gene-banks to identify useful genetic resources for OPB [82].
- Evaluate the possibility to implement prediction of germplasm performance in key locations with the aid of high throughput genotyping platforms and phenotypic information derived from multi-location testing.
- Determine if breeding perennial crops will be suitable for sustainable OF, however if crop rotation is part of the OF system, this may not be possible [83].
- Assess the incorporation of remote sensing phenotyping for traits like weed competitiveness so evaluation and selection intensity can be increased and higher genetic gains can be achieved faster.
- Undertake quantitative and association genetics research to understand both the extent of variation and genetic architecture of useful traits in OF [84–87].
- Appraise the use of cultivar mixtures to deploy host plant resistance or increase resilience in agro-ecosystems prone to abiotic stress [88].
- Judge whether the new breeding technology methods can fit into the OF principles [56, 89].

Quality traits should also be given priority for OPB: micronutrient content and plant growing and storage as they can influence grain quality [90]. Traits for low-input farming systems such as increased N-uptake and N-use [91–94] and enhanced competing ability against pathogens and weeds [95, 96] will be also important for OPB.

Abbreviations

CF: conventional farming; EB: evolutionary plant breeding; GHG: greenhouse gases; GMO: genetically modified organisms; GxE: genotype-by-environment interaction; OF: organic farming; OPB: organic plant breeding; PPB: participatory plant breeding.

Authors' contributions

LAC-H and RO did the conception and design of this article, its literature review and analysis, and manuscript writing. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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