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Plant breeding strategies for organic agriculture: A review

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Abstract
In conventional agriculture (CA), there are many inappropriate agricultural practices such as excessive tillage and use of heavy machinery, excessive and unbalanced use of inorganic fertilizers, poor irrigation and water management techniques, pesticide overuse, inadequate crop residue and/or organic carbon inputs, and poor crop cycle planning *etc*. Conversely, from past few decades changes in agriculture practices being witnessed with many farmers showing inclinations towards organic farming practices. But organic farmers are using the varieties that were developed in the background of high inorganic fertilizer and crop protection inputs. In last 60 years, crops/ varieties have been specifically developed to produce high yields under potentially unlimited use of synthetic fertilisers and pesticides. These inputs are therefore necessary to achieve optimal yields in the farmer's field. OA is one of the several approaches found to meet the objectives of sustainable agriculture. But, studies shown that varieties lack important traits required under organic and low-input production conditions. In this review the development of varieties / hybrids for organic and low-input production conditions are discussed.

Keywords: Organic agriculture, breeding traits, nutrient use efficiency

Introduction
Organic agriculture (OA) is one of the several approaches found to meet the objectives of sustainable agriculture. The organic agriculture which emphasizes using organic inputs is growing rapidly as an alternative strategy to modern agriculture. Many techniques are being used in organic farming like inter-cropping, mulching and integration of crops and livestock systems including the traditional agriculture practices (Narayan, 2005) [10]. There are several definitions of organic farming and the one given by the US Department of Agriculture (USDA) is considered the most coherent and stringent. According to it the organic farming is a system that is designed and maintained to produce agricultural products by the use of methods and substances that maintain the integrity of organic agricultural products until they reach the consumer. On the other hand, the International Federation of Organic Agriculture Movements (IFOAM) defines "Organic agriculture is a production system that sustains the health of soils, ecosystems and people". It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. The major objectivity of organic farming resides on development of a self-sustainable farming system in harmony with nature which delivers ecologically and economically sustainable pure food with enrichment of surrounding biodiversity and its entire components. The origin of organic farming is rooted in the ancient Vedic period. "In the Vedic era, there were many agricultural practices. They mostly used cow dung manure to increase the soil fertility which kept the soils healthy. There were no pesticides and to control pests, farmers used to prepare natural pesticide from neem leaves and few other leaves. However, as per the research reviews, the path breaking literature on the subject of organic farming has been published by J.I. Rodale in the United States, Lady Balfour in England and in India, Sir Albert Howard has been regarded as the father of modern organic agriculture. However, the farming being practiced for the last five decades in India has increasingly been found non-sustainable because it is more oriented towards high production without much concern for ecology. There were many inappropriate agricultural practices such as excessive tillage and use of heavy machinery, excessive and unbalanced use of inorganic fertilizers, poor irrigation and water management techniques, pesticide overuse, inadequate crop residue and/or organic carbon inputs, and poor crop cycle planning etc. Conversely, from past few decades changes in agriculture practices being witnessed with many farmers showing inclinations towards organic farming practices.

India is home to 30% of total organic producers in the world having 2.30 million ha. In financial year 2022, more than two percent of the net area in India was under organic farming. In general, the area under organic farming has increased continuously, signifying more demand for organic food at recent time. The role of organic agriculture in food security is a debatable subject considering the loss of crop productivity and increasing cost of production particularly during the transition phase. Theoretically organic farming is the best way to achieve ecologically and economically sustainable crop production and several scientific studies also support the facts with encouraging results in comparison to conventional farming. However, technological breakthrough to practically exhibit large scale economically sustainable organic production without time loss is still at large. It is estimated that more than 95% of organic production is based on crop varieties that were bred for the conventional high-input sector. Recent studies have shown that such varieties lack important traits required under organic and low-input production conditions. This is primarily due to selection in conventional breeding programmes being carried out in the background of high inorganic fertilizer and crop protection inputs. Also, some of the traits (e.g., semi-dwarf genes) that were introduced to address problems like lodging in cereals in high-input systems were shown to have negative side-effects (reduced resistance to diseases), lower protein content and poorer nutrient-use efficiency) on the performance of varieties under organic and low-input agronomic conditions. This review article throws some light on the importance of main traits required under low-input conditions. A range of breeding goals desired for the organic sector, such as yield, resistance to biotic and abiotic stress and qualities demanded by consumers do not differ from conventional breeding objectives, but it is essential that such traits are expressed under low-input conditions, which cannot be guaranteed if selection is done in high-input agronomic backgrounds. First it is necessary to describe in what respect the organic farming system differs from the conventional one to be able to stress the need for different variety traits, analyse the complex and subtle management by the organic farmer using the ecological tools available and describe the role of varieties in this context. Although organic agriculture is nowadays known for its avoidance of the use of agro-chemicals and its consequent, strive for environmental benefits, organic agriculture is more than merely replacing chemical by natural compounds. The reliability of an organic farming system depends not only on high yield levels with low inputs but also largely on yield stability. Although organic farmers may gain relatively more system stability after their conversion period and several years of good farming practices, they still have little external inputs to quickly control or correct farm conditions during the growing season against undesired heterogeneous environmental conditions in time. There is a need to optimize the organic farming system and to understand the different interactions within the system including research on the role of variety improvement keeping in mind that crop yields in organic agriculture fluctuate much more than in conventional systems.

Considerations for breeding a variety

Organic agriculture cannot be achieved easily by centralised breeding programme as it has to look into several aspects. In OA systems plants have to form and maintain a larger and more active root system for nutrient uptake (i.e. have to be efficient in acquiring nutrients) and will depend more on interaction with beneficial soil micro-organisms that promote nutrient uptake. Therefore organic farmers require varieties that are (1) adapted to such a specific low input soil management and efficient in nutrient and water uptake, (2) have adequate root system architecture, and (3) can interact with beneficial soil micro-organisms. Moreover, such varieties need to be efficient in the use of nutrients and water, *i.e.* yield relatively large amounts of desired products per unit nutrient and water taken up by the plant. Such varieties are directly related to higher yield levels. To attain yield stability organic farmers require varieties adapted to lower and organic input conditions. However, some modern varieties require high nitrogen levels to realize their high-yield potential. Adaptation of varieties to organic inputs means that the varieties grow at a regular growth rate, showing that they can cope with less controllable and more fluctuating nitrogen-dynamics without resulting in irregular crop development causing inferior quality due to diseases or disorder. Wolfe *et al.* (2008) [17] differentiated three different potential approaches to obtain crop varieties suitable for organic agriculture: (1) breeding programmes focused on the needs of conventional agriculture where selection is carried out under conventional farming conditions, an approach requiring farmers to test varieties and select the ones that perform well under organic conditions, (2) varieties derived from conventional breeding programmes where crosses and early selection are focused on traits required in conventional systems, but where later or advanced breeding generations are evaluated and selected under organically managed farming conditions, and (3) varieties derived from breeding programmes where crosses and selection strategies focus on traits demanded by the organic sector and selection is carried out in the background of organic farming conditions. The level of breeder-driven and farmer-driven activities may differ in these three breeding approaches. There are also farmers who use their own selection programmes based on older (regional) varieties or landraces. It is necessary to combine (1) resistance to diseases that remain a problem in organic and low-input systems (i.e., Septoria, Fusarium, rusts, bunt), (2) resistance to abiotic stress factors (drought and low nutrient levels) and (3) quality traits.

The greatest difference between organic and conventional systems relates to soil management practices used and to processes in the rhizosphere. Organic system depends on organic matter based fertilizer inputs and mineralization-driven N and P supplies to crops. Macronutrient availability patterns during the growing period therefore differ significantly from those in conventional systems. Organic crops often experience limited macronutrient (N and P) availability especially during periods when soil temperatures and water availability reduce mineralization capacity by the soil biota. However, regular organic matter inputs have shown to increase soil biological activity and biodiversity and associated mineralization capacity of the soil. Organic system prefers crop genotypes that are able to form active symbiotic relationships with beneficial organisms in the rhizosphere, and thereby establish mechanisms that increase nutrient-use efficiency (e.g., vigorous root systems, ability to form active mycorrhizal associations, reduced root losses due to pathogens, ability to maintain a high mineralization activity in the rhizosphere via root exudates, increased rooting depth and associated ability to recover N leached from the topsoil.

Nutrient-use efficiency

Today, many agricultural breeding programs are conducted in environments where inputs such as nitrogen fertilizers are highly regulated to ensure that crop deficiencies are minimized. So studies on the NUE of plants and populations in natural ecosystems helps in designing selection regimes and identifying specific traits that are useful for improving varietal performance in low-input and organic systems. In OA, root systems should be able to explore deeper soil layers and be more active than in conventional systems. Organic farmers need varieties with deep root systems that can strive under stressful soil environments and can able to exploit unpredictable conditions. To compensate for the relatively low N availability in OA systems, the potential for grain protein production has to be higher than in conventional agriculture by total N uptake into the grain has to be improved in order to maintain yield levels *i.e.,* superior in N extraction in low-N environments. Improving the different compounds of nutrient-use efficiency, like maintenance of photosynthesis under nutrient stress, nutrient-uptake capacity, nutrient-utilization capacity and translocation efficiency, will contribute to higher yield and quality under low-input conditions. For organic farming, the adaptation of varieties to efficient nutrient-use derived from slow-nutrient-releasing organic fertilizer is of special importance, which is not addressed in conventional selection programmes with no or less inorganic fertilizer (Dawson *et al*., 2008) [5]. Nutrient-uptake efficiency of plants can be improved by the capacity of crops to establish and sustain efficient (1) plant-growth-promoting-rhizosphere (PGPR) bacterial communities (Wissuwa *et al*., 2009) [16] and arbuscular mycorrhizas (AMs), a trait that has been described as “rhizosphere competence”. PGPR-bacteria promote N-uptake efficiency since they protect root systems against attack by soil-borne pathogens (2) maintain efficient mineralization-driven nutrient supplies to plant roots (Rengel and Marschner, 2005) [13] and (3) support the establishment of active AM associations. AMs are essential for efficient phosphorus, micronutrient and water uptake in plants grown under organic (Gosling *et al*., 2006) [8] and low-input conditions.

Resistance to soil- and seed-borne diseases and/or mechanisms to maintain disease suppressive organisms (e.g., plant-growth-promoting rhizosphere (PGPR) bacteria, AM-fungi) in the rhizosphere are important traits in organic production because healthy root systems are required for crops to express their genetic potential for nutrient-use efficiency and yield. Suppressive effects are provoked by a range of different mechanisms including (1) antibiosis, (2) site and nutrient competition, and (3) induction of resistance in the crop plant (Whipps, 2001) [15].

Weeds often are mentioned as the most significant problem in organic farming systems and they are certainly the problem that most concerns the farmers who are considering converting their conventional farm into an organic one. Because no herbicides are allowed in organic farming systems, more emphasis is on prevention, decision making (timing) and weed control technology. In weed management, genotypic ability to compete with weeds is an important factor. So it is required to select a genotype having high seedling vigour at early stages to compete with weeds for growth and also higher grain yield and weed suppression ability (WSA). Traits associated with high ground cover include rapid early growth rate are important one. So organic farmers require varieties that have a rapid juvenile growth and the ability to cover or shade the soil in an early stage of crop development to outcompete weeds for light. Allelopathy is another potentially important weed suppression trait that has received little attention in recent years. Allelopathy is a chemical process where plants provide themselves with a competitive advantage due to the direct or indirect effect on germination, growth or development of neighbouring plants. Wu *et al*. (1999) [18] suggested that the identification of varieties with high allelopathic activity and the transfer of such a characteristic into modern varieties could restore an important trait that has inadvertently been lost during the process of selection for higher yields. Apart from practical experiences, in most cases information is lacking on growth characteristics of varieties that contribute to competitiveness, indicating that so far weed competitiveness has received little attention from breeders. Resistance to seed-borne diseases in organic seed production is an important issue as few seed treatments are permitted for use under organic farming standards. Tolerance to diseases that may cause injuries and are likely to affect plant health and quality is crucial for minimizing the gap between yield potential and actual yield. This applies to conventional high-input as well as to low-input or organic farming. Resistance breeding combined with appropriate management approaches (e.g., diverse rotations, timely sowing, and improved irrigation methods) can minimize losses caused by such pathogens. Dordas (2008) [6] reviewed the effect of the nutrients N, P, K, Mn, Zn, B, Cl and Si on disease resistance in sustainable agriculture. At high N levels the severity of infection with obligate parasites increases, while infection with facultative parasites decreases and concluded that a regulated nutrient supply will limit disease severity. Insect resistance: Because insecticides are not permitted under organic farming standards, organic growers use alternative measures. Examples of cultural management tools are e.g., the establishment of beetle banks to maintain high predator or parasite populations; companion plants to repel or distract pests; mass trapping systems, pheromone-based mating disruption. But also alternative treatments can be applied (e.g., BT) and barrier-based approaches to control invertebrate pests (most importantly the use of insect-proof netting). Tolerance to abiotic stresses is important not only for organic but also for conventional agriculture (CA). In some cases such as drought stress, organic farmers may give higher priority to such traits as they want to build up a system that is less dependent on inputs.

Important traits

1. Early crop vigour is associated with increased competitive ability (Rebetzke and Richards 1999; Pester *et al*. 1999; Lemerle *et al.* 2001, b; Acciaresi *et al.*, 2001; Bertholdsson, 2005) [12, 11, 9, 1, 3].
2. Plant height is widely reported as an important trait for increasing crop competitiveness (Gooding *et al*., 1993) [7]. The relative importance of plant height decreases if compensated for by other traits. For example, a short planophile genotype with rapid leaf canopy development and high leaf area index may have higher weed suppression than a tall genotype without these other traits. Above-ground competitiveness integrated with improvements in nitrogen use efficiency, root

competition and allelopathy (Bertholdsson, 2005) [3].

3. In conclusion, OA needs resistance breeding, but the overall approach, together with the pattern of diseases and their significance, is somewhat different from conventional farming. OA in general aims at a broader approach to disease resistance combining morphological and physiological traits to ensure overall plant health instead of absolute, specific resistance.

   There is no doubt that field trials to compare varietal performance under organic and conventional conditions have provided valuable information, confirming that there can be both differences and similarities, with some varieties showing consistent adaptation to OA or to CA or to both. However, it is also clear that the kinds of difference and their scale are dependent on many factors, the most important being the exact type of OA or CA system. For this reason, it may be important to continue with trials comparing variety performance in OA and CA, unless there is a highly specific objective. Currently, organic farmers are making use of the most appropriate varieties produced in CA programmes. In the practical observations that varieties bred under organic conditions are efficient in high resource and higher yielding, when used in CA also (Burger *et al*, 2008) [4].

Conclusion

Breeding for OA is limited to a handful of small-scale breeders. Because of increasing input costs, increasing impact of climate change and the need for sustainability are creating a larger opportunity for the specific breeding objectives. The organic sector is differentiating roughly into three scales, Global Commodity, Regional and Local Market. Until recent varietal development still tends to be a one-way traffic, varieties bred for CA being screened for use in OA. In particular, the global commodity market is supplied mainly with such varieties. Smaller scale programmes, including breeding directly for OA, tend to be directed towards regional and local markets. Many of the characteristics required in new varieties are common to both CA and OA, there are a number of characters have a higher priority in OA. These include characters that are important for the farming system and the crop rotation, for example, weed competition and adaptation to arbuscular mycorrhizas. There is also a need for simultaneous selection of characters such as weed competition, nutrient uptake and disease and pest resistance, which are often helped by positive interactions from early plant vigour. Study is needed for nutrient uptake and use efficiency. For nitrogen, this needs to include improvement of relationships between crop and nitrogen-fixing organisms living either on roots or free-living; a similar study applies to phosphorus also. Breeding for disease resistance differs from the CA approach, with the need for plant vigour to encourage general plant health, together with more specific approaches for resistance to seed-borne diseases. However, all these characteristics may be combined; there will be a need under the conditions of OA to deal with large genotype-environment interactions. For this reason, the potential for decentralised breeding, to select plants in the places that they will be grown, is particularly important for Organic Plant Breeding, combined with Participatory Plant Breeding at different levels from breeder to farmer. The most important tool that helps in highly variable environments is the use of genetically diverse crops, including inter-cropping, mixtures and populations, which will play larger roles in OA. Such approaches can also be valuable in helping to restore or increase biodiversity within the crop. The selection for adaptation to organic farming systems should preferably be done under organic conditions only.

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