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Genetic Improvement of Agronomic Important Traits for Organic Agriculture

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To feed the ever-growing populations, crop productivity needs to produce more food. Under intensive agriculture, non-judicious use of chemicals is being applied, which leads to serious health concerns for humans, animals, and the environment. Natural or organic agriculture is an age-old farming practice that largely excludes chemical fertiliser, pesticide, and synthetic growth regulator use. Organic farming produces high-quality food and focuses on nutrition, agor-biodiversity, resource recycling, soil carbon, cost, employment, and productivity (Reganold et al., 2016). However, organic farming is often criticised for its low productivity and profitability and always puts question tags on its broader implications in modern agriculture. Plant breeders play a significant role in producing high-yielding crop varieties resistant to biotic and biotic stresses and indirectly promote natural or organic farming. Plant breeding also played a significant role in minimising the gaps between intensive farming and organic farming systems. Organic plant breeding focuses on farming systems' quality, yield and resilience. The ultimate goal of any plant breeding programme is to develop varieties with a high degree of resistance to biotic and abiotic stresses, high yielding, and early duration. However, for organic breeding, breeding objectives such as local adaptations, high water and nutrient use efficiency, weed competitiveness, synergistic effect in agroforestry, mixed cropping, and yield stability are required in addition to general plant breeding objectives. Varieties developed by conventional breeding are high yielding, input responsiveness, and primarily not being focused on organic farming. Organic breeding is a comprehensive approach focusing on crops' end product and overall plant growth and development. Organic breeding involves a holistic approach in which technical, socio-economic, and ethical issues must be considered before breeding crop varieties. Organic breeding approaches should harmonise with the four IFOAM principles: care, ecology, fairness and health (Nuijten et al. 2017). To fulfil the IFOAM principles in organic breeding, all stakeholders must take due consideration into account, i.e., Farmers, manufacturers, consumers and breeders.

Organic plant breeding refrains from all those methodologies or technologies that utilise DNA recombinant technology, cell fusion or protoplast fusion. Under organic breeding, natural plant reproduction ability is respected, and therefore, no terminator seed technology is allowed to commercialise the products. The application of molecular markers for particular issues like the pyramiding of multiple disease resistance genes and the indirect selection of critical economic traits from the population may be used. In organic breeding, resistant cultivars or lines have been developed through diverse multiple genes, crop diversity and synergistic interaction of plant-microbe interaction. Organic breeding is a systematic process involving crossing, selecting and evaluating lines strictly under organic conditions. Landraces are a source of diversity and have adapted to local conditions. They are potentially an essential resource for organic breeding. Participatory breeding or participatory varietal selection is a critical component in organic breeding for the development of broader acceptability and preference varieties. The target of key traits imparted in organic conditions is crucial and always a prime objective while breeding organic varieties. The novel traits suited for organic conditions would be explored using long-term trial and simulation studies. Developing crop ideotypes, especially for organic breeding, would lead to developing varieties with broader adaptation, input responsiveness, improved root system, weed tolerance, and healthy soil–microbe interaction with high-quality produce. Organic farming is still in the germinal phase in many countries; however, demand for organic food is increasing daily, mainly from developed countries. The success of organic breeding depends upon the government's policy, financial support, market accessibility, and socio-economic and ethical aspects.

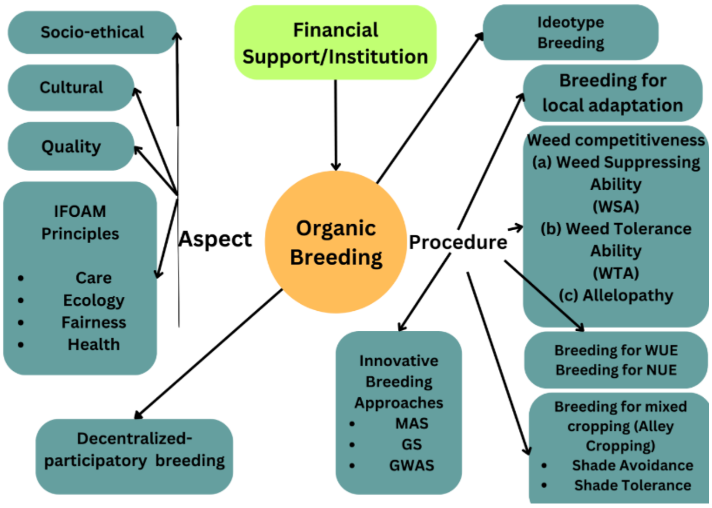

Fig. 1 Holistic view of organic breeding scheme

Breeding for organic or low input conditions

Breeding for local adaptation and yield stability

Local adaptation refers to populations that perform better and have higher fitness, vigour and meaning in their original or native environment than in other environments. Adaptation to local environmental conditions began from early domestication and selection or by human-managed environment. When crop species moved from their origin, crops developed inherent adaptation to local edaphic conditions, leading to the development of several landraces and cultivars. Local adaptation is one of the critical components of organic breeding, as the quality of input dramatically varies from place to place. Locally adapted varieties will have specific adaptations to the local environment and perform optimum under locally available organic inputs. Breeding for specific or local adaptation is one of the most sustainable and viable strategies for breeding varieties performing well under high input conditions (Ceccarelli, 1996). Breeding for organic or low input responsiveness conditions requires identifying and selecting population similar to the prevailing conditions of farmers. While breeding for local adaptation, deciphering the genetics of local adaption is a primary requisite. The Genetics of local adaptation reflect that it results from allelic trade-offs at individual loci where local alleles are favoured in the local environment and unfavoured or selectively neutral in other environments. Yield stability under fluctuating climatic conditions is a crucial consideration in organic agriculture.

Breeding for weed tolerant or weed competitiveness

The primary objective of plant breeders is to develop high-yielding varieties with resistance to disease and insect pests. Non-judicious use of herbicide can cause the development of super weed, which poses a severe threat to the environment. Weed-suppressive or tolerant genotypes could be an alternative to herbicides (Lemerle et al., 1996). Competitiveness against weeds may often be more important than yield potential in organic systems. The presence of adequate genetic variability, genetics, and gene action of the traits must be available for genetic improvement of weed suppressive ability. Variation in weed suppressive ability has been observed in many crop species (Bertholdsson, 2005) and varieties of the same species. Tolerant varieties or cultivars can suppress weed growth and reproduction and give reasonable yield and biomass. Traditional varieties or landraces have been reported to have more weed competitive ability than modern varieties due to numerous traits such as vigour, tallness and high leaf area index. Weed competitiveness cultivars can co-exist with weeds and give reasonable yields or surpass them in terms of fitness and vigour. The competitive ability of weed-tolerant genotypes is conferred by a combination of different morphological and physiological traits, enabling the crop genotypes to access more resources (nutrients, water and light) than the weeds. The selection of weed-suppressive variety is made either through direct selection under weed-free nurseries or through indirect selection via identification of key traits that have high heritability and positive association with weed suppression ability. A competitive weed ideotype for different crops can be developed through a simulation model or discriminate function analysis.

Competitive ideotype combines several morphological traits that directly or indirectly contribute towards weed suppression. In recent years, competitive ideotypes for weed tolerance have been identified in several significant crop species, i.e. rice, wheat and maise. Rice lines with vigorous tillers, high biomass production, and high leaf area index have been identified as having more incredible weed suppressive ability in West Africa. (Johnson et al., 1998). A wheat variety with high tillering ability, tall, high leaf area index (LAI), performed well in monoculture and had reasonably good yield in weed nurseries. Trait selection for the hypothesis of ideotype significantly varies from species to species and environment to environment. For yield maximisation under organic conditions, competitive ideotypes also have inbuilt resistance or tolerance to various biotic and abiotic stresses.

Allelopathy is another mechanism by which crop plants suppress weed growth by releasing toxic exudates that harm the growth and development of weeds. In addition to direct evaluation for weed competitiveness, breeders must screen all the available germplasm for variation in allelopathy effect. Significantly less attention has been paid to deciphering allelopathy genetics and its utilisation in breeding programmes. In some research, traditional primitive rice landraces have been found to be more allelopathic than the present-day modern cultivars (Fujii, 1992), while in another study, modern high-yielding varieties (HYVs) are reported to be more allelopathic than older cultivars (Courtois and Olofsdotter, 1998). In several crop plants, higher allelopathic effects are found in tertiary gene pools or wild relatives. Therefore, wide hybridisation is also one of the breeding tools that can be exploited to enhance the allelopathic effect. Marker-assisted selection (MAS) allows one to map and introgress QTLs of high phenotypic variance for allelopathic effect. The efficiency of MAS depends upon the availability of a suitable mapping population, molecular makers, and phenotyping and detection methods. Regulatory gene also plays a significant role in controlling the expression of allelopathy effect under stress and normal conditions.

Breeding for complex traits (Mixed cropping, agroforestry/alley cropping)

The selection of varieties or lines that have specific adaptations to intercropping or mixed cropping is a significant challenge for a plant breeder because of the enhancement of the land equivalent ratio (LER). The performance of a genotype in pure stand or a mixture dramatically varies among species and genera. Adapted genotypes have better buffer capacity and unleash the full genetic potential of mixed cropping in terms of economic yield and stability. The choice of genotypes for mixed cropping within each species is not defined. Hence, rigorous exercise is required to identify suitable mixing partners for mixed cropping. Direct selection for yield under mixed cropping is reported to have low heritability and affect the overall efficiency of the breeding programme. Varieties with high general mixing ability (GMA) provide high yields under mixed cropping, while varieties with high specific mixing ability (SMA) yield well under specific mixing partners. Breeding of mixed cropping largely depends upon the model that estimates GMA and SMA variance, choice of efficient design, analysis and linking of traits, and uncovering biological interaction function of the traits (BIF). For environment conservation and enhancing productivity under organic and low input conditions, agroforestry provides an opportunity to utilise its sustainably and make silvo-arable agroforestry systems more productive and remunerative. Crop varieties are generally bred for open fields, and when planted under the agroforestry model, their yield and biomass performance are reduced. However, plant breeding has immense potential to breed varieties that can adjust in silvo-arable agroforestry model and have a minimum reduction in yield. Pardon et al. (2017) have observed adequate genetic variation among crops and varieties for silvo-arable agroforestry. He observed that winter wheat and barley varieties are less sensitive than spring crop varieties. Tolerant varieties compete through efficient utilisation of light, water and nutrients. Under the alley or agroforestry model, the evaluation of varieties for better competitiveness can be identified and utilised in the breeding programme. Breeders also look to develop shade and drought-tolerance crop varieties with enhanced symbiosis.

Breeding for efficient nutrient use efficiency (NUE)

Under organic or low input conditions, rhizospheric activities are crucial in nutrient acquisition and mineralisation. Genotypes with vigorous and flexible root growth and better mycorrhizal interaction can efficiently utilise water and nutrients from deeper soil layers. Significant variations in nutrient use efficiency, particularly nitrogen use efficiency (NUE) and phosphorous use efficiency (PUE), have been reported for many crops. A genotype with high nutrient use efficiency (NUE) gives a reasonable yield in both optimum and low-input agriculture. The breeder's role in developing high NUE varieties is crucial for optimising resources, as well as the sustainability and profitability of farming systems. Assessment of genetic variability, especially for root traits, is crucial before designing a breeding programme. More efficient varieties develop through modification of root morphology, physiology, efficient translocation and internal utilisation. The presence of specific micro-organisms can influence rhizospheric activity and enable the root systems to acquire more water and nutrients. AMs are essential in water absorption mobilisation of phosphorus and other micronutrients grown under organic and low-input conditions. Several QTLs/genes have been identified and mapped in several crop plants for mycorrhizal root symbiosis. Although manipulating genes for microbial association is cumbersome, recent advancement in molecular breeding technologies can provide ample opportunity to utilise these genes for better nutrient-use efficient varieties. Overall, in developing varieties for efficient nutrient use efficiency (NUE), collaborative research is needed involving agronomists, crop physiologists and biotechnologists.

Breeding for durable resistance/ tolerance against diseases and insect pests

Under organic or low input conditions, farmers have hardly any curative measures to protect the crops from diseases and insect pests. Disease management is done through various means, such as cultural, physical, botanical, or resistant varieties. However, developing varieties is one of the sustainable strategies to get higher productivity under organic and conventional farming. All breeding procedures, like trait selection, crossing, evaluation and selection, should be done in the target environment for broader adoption. Various protection measures are applied to control soil-borne diseases, insect pest and nematodes, i.e. crop rotation, soil amendment and other cultural practices. In cases where cultural control measures are not beneficial, resistant varieties can offer an alternative for crop protection. Organic farming starts with organic seeds that must be free from disease and insect pests. For seed production under organic conditions, the focus should be on developing varieties that have resistance with primary seed-borne diseases and insect pests under field and during storage conditions. Plant traits that promote resistance to foliar diseases must be considered while designing ideotypes for disease resistance in cereals. Plant architecture traits are one of the critical targets for the breeder while selecting genotypes for foliar diseases. Minor leaf genotypes in barley and wheat have been reported to have lesser infection for foliar fungal diseases. Plant morphological, anatomical and physiological traits with avoidance and defence mechanisms must be explored to diversify breeding approaches and develop multiple durable resistance varieties.

Innovative breeding approaches under organic breeding

Organic breeding approaches account for socio-economic, agroecological, geographical, and institutional perspectives. It works harmoniously with IFOAM principles, and therefore breeding methodologies/principles vary somewhat from conventional breeding. Genome modification approaches like genetic engineering and genome editing are incompatible with organic breeding. Marker-assisted selection (MAS) is routinely used in breeding programmes to select traits through DNA markers indirectly. The use of molecular markers under organic breeding was extensively elaborated by Wolfe et al. (2008). He has classified the breeding programme into three categories, *ie.* Breeding programme for conventional agriculture (BFCA), breeding programme for organic agriculture (BFOA) and breeding programme within agriculture (OPB). BFOA activities operate under normal conditions and only at the last stage of breeding procedures, where testing is done under organic conditions. In OPB, the whole breeding process ie crossing, selection, and evaluation, must be done under organic conditions. The use of molecular markers also significantly differs in both stages; BFOA utilises molecular markers similar to BFCA, while in OPB, molecular markers are restricted to some extent. In OPB, molecular markers are used as an additional tool and can be used in the last stage of testing for complex traits. With advancements in sequencing technologies, genomic selection becomes more convenient than phenotyping of a large population. However, genomic selection (GS) success depends upon the training population, model use and genotyping data. The use of genomic selection in OPB is still debatable due to the selection of plants at the genotypic level, and the population is not exposed to organic conditions.

Conclusion

With recent progress in organic farming conditions, plant breeders have a significant role in developing or identifying important agronomic traits specifically suited for organic consideration. While breeding, it is also essential to consider all aspects, i.e. social, ethical, and agro-geographical, for broader adoption and implication of organic agriculture. Traits that impart some degree of competitiveness under organic conditions must be exploited in breeding programmes to develop location-specific varieties or hybrids. Traditional varieties of several crops have some inherent attributes that contribute to organic farming. A multi-disciplinary team involving breeders, physiologists, agronomists or other relevant disciplines is needed to frame a research proposal for organic conditions that will help in environmentally friendly organic varieties. Recent progress in advanced breeding technologies like marker-assisted selection, genomic selection, and wide association studies has further enhanced the scope of organic breeding for the indirect selection of traits. Overall, the progress of organic breeding depends upon socio-ethical considerations, regulatory frameworks, financial support, and government policy decisions.

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