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Review

Orphan crops for future food security

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Climate change, along with current agricultural practices, is going to pose a significant challenge for future food security, especially in developing countries. Orphan crops can help mitigate this threat due to their inherent properties of stress tolerance and nutrition content. Industrialization of agriculture has left these minor crops behind in terms of domestication. As a result, the potential of these crops is underutilized. These crops can be a game-changer in the long term if necessary steps are taken to improve the quality as well as quantity of yield. Concerted efforts by many groups around the world have been taken for research and development of these crops. Besides, the unique properties of these crops have caught the media attention, which hails these crops as superfoods. Favourable government policies to promote these crops can help in the large-scale adoption of these crops by the farming community. Besides, the stress-resilience of these crops can help boost the sustainability of agriculture and ensure food security for future generations.

Keywords. Food security; genetic resource; healthy food; orphan crops; stress tolerance; sustainable agriculture

1. Introduction

Humanity is facing immense problems with the exponential increase in the population and shortage of land. As a result, there is a significant threat to food security in the future. According to estimates, food production must be increased by at least 70% by the year 2050 to support the increasing world population (Godfray *et al.* 2010a). Unpredictable climate change has caused frequent stresses, such as drought, salinity and extremes of temperature, making it challenging for growers. Apart from these abiotic stresses, plants also face challenges from biotic stresses, such as bacteria, fungus, viruses, nematodes, etc. Thus, all these biotic and abiotic stresses lead to huge yield loss (Godfray *et al.* 2010b). Hence, there is an utmost need to focus on plant varieties with improved stress tolerance, yield and nutrition to ensure food security for the coming generations.

Crop production is governed by various factors, which can be manipulated to boost productivity. The arable land is limited due to increasing urbanization and lack of water for irrigation. Intensification of agriculture is another option, which can lead to increased yields per unit of land. The Green Revolution was the result of agricultural intensification which witnessed large-scale use of fertilizers and pesticides, agricultural machines and genetically enhanced high-yielding varieties (Pingali 2012). Cereal crop production saw a great boost and yields almost tripled without any significant increase in land area under cultivation (Martin *et al.* 2019). However, agricultural intensification has its own ecological cost. Excessive use of fertilizers and pesticides have disrupted the natural nitrogen and phosphorus cycles and contributed to pollution, diseases and biomagnification (Foley *et al.* 2011). The risk of disease outbreaks has increased due to monocultures (Zhu *et al.* 2000). Besides, cultivation

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of only a few crops, such as rice, wheat, maize and soybean, has been intensified. Since these high-yielding modern varieties have a narrow genetic base, they are more prone to different kind of stresses. Hence, there is an urgent need for the development of varieties that are high-yielding, stress-tolerant and can be cultivated sustainably without excessive burden on the limited agricultural resources.

Sustainable agriculture is the need of the hour. This can be achieved either through breeding programmes or transgenic approaches. However, both methods have their limitations. Breeding programmes often focus on one character, such as high yield or stress tolerance, and hence, other essential characteristics are lost. Also, the process is time-consuming and may take up to 5–10 years for the release of a variety for use by farmers. Most of the breeding programmes utilize wild relatives or traditional landraces for favourable alleles (Dwivedi *et al.* 2016; Zhang *et al.* 2018). While the past breeding efforts led to the generation of high-yielding varieties, the current efforts to improve stress-tolerance has not produced any significant results due to the complexity of stress response in plants (Mittler 2006; Tardieu *et al.* 2018). Advances in biotechnology have made the transgenic approach a viable option to produce crops for the future. Considerable knowledge has been generated regarding biotic and abiotic stresses in plants (Roy *et al.* 2014; Hu and Xiong 2014). Numerous useful genes and quantitative trait locus have been identified, which can serve as a viable option to boost the stress tolerance of crops. The transgenic approach is the more favourable approach due to its precision and shorter development time compared to breeding. Most of the genetically modified crops in the market having traits, like herbicide and insect tolerance in corn, cotton and soybeans, have been raised using a transgenic approach. The complexity of stress tolerance mechanism, coupled with the variation in its severity, timing and duration, has made it hard to find a single- or multiple-gene transgenic approach for stress tolerance. However, it still has a few drawbacks, like the loss of the transgene over generations, and use of constitutive promoters. Besides, the commercialization of transgenics is hindered by the stringent regulatory mechanisms (Rothstein *et al.* 2014).

The increasing world population, coupled with climate change, has made it imperative to increase the production of nutritious food sustainably and profitably. Change in climatic agro-climatic conditions, associated with shifting food habits throughout the world, has led to the search of alternate crops, which are nutritious as well as suitable for the future agro-climatic conditions. Hence, it is imperative to be proactive and search for alternatives which are ready for the future agro-climatic conditions. Natural selection has produced a plethora of highly nutritious crops that are also stress tolerant. Many of these crops have been domesticated, while some still grow in the wild. These are often grown by small farmers locally and have not found favour among the farmers globally due to the dominance of other crops, mainly maize, wheat and rice. However, these crops are gaining popularity among researchers as well as farmers. This review aims to highlight the importance of crops which can become our primary food source in the coming decades, and ensure food security through sustainable agriculture.

2. Search for alternative food sources

Plants are among the most evolved organisms on this planet and have colonized almost every corner of the earth, including the most hostile ones. Extremophiles are plants which grow in the most stressful conditions, such as xerophytes and halophytes. These plants have evolved unique mechanisms to adapt to their respective environments. For example, xerophytes like cacti have thorns and succulent stems. However, such extremophiles are not suitable as regular food crops. However, they can serve as excellent model systems to understand the various mechanisms which these plants employ to survive in the harsh environments, and consequently, this knowledge can be translated to increase the stress tolerance of major crops.

Suitable alternative crops which can replace and/or substitute the regular food crops should have certain desirable characteristics, such as being nutritious, nontoxic and sustainable. Besides, if the crop is evolutionarily close to the current major crops, it is an added advantage. Plants which were domesticated early in the course of human evolution can serve as alternatives due to their reasonably good yields without any of the modern agricultural inputs, such as fertilizers and pesticides (Miller *et al.* 2016). These minor crops, also known as orphan crops, have the potential to serve as food crops and solve the issue of future food security.

3. Orphan crops

Orphan crops have recently gained prominence for being stress tolerant and nutritious (table 1). They have been called by different names, from 'lost' and 'neglected' crops to 'promising' and 'superfoods' (Tadele 2019). Orphan crops were once the source of

Table 1. Orphan crops and their characteristic features

S. No.	Orphan crop	Scientific name	Characteristic trait	References
1	African rice	*Oryza glaberrima*	Stress tolerant	Linares (2002)
2	Amaranth	*Amaranthus spp.*	Nutritious	Arêas *et al.* (2016)
3	Bambara groundnut	*Vigna subterranean*	Nutritious; Drought tolerant	Mayes *et al.* (2019)
4	Barnyard millet	*Echinochloa crus-galli*	Abiotic stress tolerance	Upadhyaya *et al.* (2016)
5	Buckwheat	*Fagopyrum esculentum*	Nutritious	Wijngaard and Arendt (2006)
6	Cassava	*Manihot esculentum*	Drought tolerant	Ceballos *et al.* (2004)
7	Chickpea	*Cicer arietinum*	Nutritious	Mafakheri *et al.* (2010)
8	Cowpea	*Vigna unguiculata*	Nutritious; Drought tolerant	Timko and Singh (2008)
9	Enset	*Ensete ventricosum*	Drought tolerant	Olango *et al.* (2014)
10	Finger millet	*Eleusine coracana*	Abiotic stress tolerance	Pragya Singh (2012)
11	Foxtail millet	*Setaria italica*	Abiotic stress tolerance	Taylor and Kruger (2016)
12	Grass pea	*Lathyrus sativus*	Nutritious; Extreme drought tolerance	Girma and Korbu (2012)
13	Horsegram	*Macrotyloma uniforum*	Nutritious	Chahota *et al.* (2013)
14	Kodo millet	*Paspalum scrobiculatum*	Abiotic stress tolerance	Upadhyaya *et al.* (2016)
15	Lentil	*Lens culinaris*	Nutritious	de la Vega *et al.* (2011)
16	Linseed	*Linum usitatissimum*	Nutritious	Zuk *et al.* (2015)
17	Little millet	*Panicum sumatrense*	Abiotic stress tolerance	Upadhyaya *et al.* (2016)
18	Okra	*Abelmoschus esculentus*	Nutritious; Biotic stress tolerant	Kumar *et al.* (2013)
19	Pearl millet	*Pennisetum glaucum*	Abiotic stress tolerance	Yadav *et al.* (2016)
20	Pigeon pea	*Cajanus cajan*	Nutritious	Jeevarathinam and Chelladurai (2020)
21	Proso-millet	*Panicum miliaceum*	Abiotic stress tolerance	Taylor and Kruger (2016)
22	Quinoa	*Chenopodium quinoa*	Nutritious	Collar (2016)
23	Sweet potato	*Ipomoea batatas*	Nutritious	Lebot (2019)
24	Tef	*Eragrostis tef*	Gluten-free; Abiotic stress tolerant	Spaenij-Dekking *et al.* (2005)
25	Yam	*Dioscorea spp*	Drought tolerant	Raymundo *et al.* (2014)

livelihood of small and marginal farmers. However, the intensification of agriculture led to a drastic decline in their cultivation. These crops are more efficient users of water and soil nutrients. Besides, they are more tolerant to various abiotic stresses, such as drought, and are also resistant to multiple diseases and pests. Hence, these crops are more suitable for sustainable agriculture. However, the yields of these orphan crops are comparatively less than the major crops due to lack of intensive breeding efforts. Since these crops have not been fully domesticated, there is considerable scope for genetic improvements which can further boost their yields while still maintaining stress tolerance (Goron and Raizada 2015; Bazile *et al.* 2016).

4. Diversity of orphan crops

Orphan crops include cereals, fruits, vegetables as well as root crops. Drought and salinity are two of the major abiotic stresses that are affecting food production globally. Some of the potential orphan crops which can substitute or replace traditional crops have been extensively reviewed earlier (Tadele 2019; Mabhaudhi *et al.* 2019). Apart from being better suited for harsh environmental conditions, these crops are highly nutritious and are being promoted exclusively as healthy foods.

Millets are one of the most important cereal crops; there are many different types of millets, including pearl millet (*Pennisetum glaucum*) and foxtail millet

(*Setaria italica*). They are mostly grown in African and Asian countries as a staple food crop (Habiyaremye *et al*. 2017). These are known for their drought tolerance, but are also resilient to salt stress and have excellent water and nitrogen use-efficiency (Goron and Raizada 2015). However, they have lacked widespread adoption due to low yields and lack of regional cultivars.

Quinoa (*Chenopodium quinoa)* is a halophytic plant known mainly for its extreme tolerance to salinity. Mostly grown in nitrogen-deficient areas of the South American continent, it exhibits resistance to cold and drought as well. Its cultivation has increased over the last few decades, and efforts are being done to sequence the different ecotypes and to develop high-yielding varieties (Zou *et al.* 2017).

Pseudocereals such as grain amaranth (*Amaranthus hypochondriacus*) and buckwheat (*Fagopyrum esculentum* and *Fagopyrum tataricum*) are known to grow in nutrient-deprived soils. Besides being resilient to various stresses, they also have many potential health benefits (Zhang *et al.* 2017).

Orphan legumes crops are essential sources of protein and can be easily grown in nutrient-poor soils. Cowpea (*Vigna unguiculata*), chickpea (*Cicer arietinum*), grass pea (*Lathyrus sativus*) and Bambara groundnut (*Vigna subterranean*) are some of the important legumes which are mostly grown in Asian and African countries. Being extremely tolerant to drought and other stresses, these crops are grown as insurance against the failure of other crops (Sanginga *et al.* 2000).

Oilseeds such as sesame (*Sesamum indicum*), linseed (*Linum usitatissimum*) and castor bean (*Ricinus communis*) are mainly grown as niche crops. Root crops such as cassava (*Manihot esculentum*) and sweet potato (*Ipomoea batatas*) are grown as a food source in many developing countries, mainly due to their drought tolerance and ability to thrive in poor soils (Tadele 2019).

5. Significance of orphan crops

Orphan crops can be a lifesaver for the millions who go to bed hungry every night. Apart from being nutritious, these orphan crops can be grown with very little agricultural input. Also, being stress-resilient, these crops are safe from the various vagaries of climate change and ensure yield even when other major crop varieties fail. These crops can help ensure food security for small farmers. Besides, orphan crops also bring diversity in agriculture and serve as resource material for agricultural research to further increase the stress-tolerance of major food crops. These orphan crops also favour the shifting food habits of the modern generation.

5.1 *Diversification of agriculture*

World agricultural production is dominated by three major crops, i.e. maize, wheat and rice., which constitute almost 50% of calories and protein consumption. Besides, just 30 plant species are responsible for producing nearly 95% of the food globally (Shelef *et al.* 2017). Hence, it is evident from the number of crops being grown and the diversity among the major crops, that biodiversity has drastically reduced over the last few decades (Cardinale *et al.* 2012). At present, agriculture has become homogenous, and monocultures are being grown over globally over large areas. This makes crops more susceptible to outbreaks of various diseases and pests (Altieri *et al.* 2015). Also, excessive use of fertilizers and pesticides are altering soil characteristics and polluting water sources. Hence, there is a need to promote sustainability in agriculture.

Orphan crops can solve many of the problems of modern agriculture and help make the practice more sustainable. These crops can ensure stable yields even during stress conditions when major crops fail to deliver. Since most of these crops are suited to grow in poor and marginal lands, minimal fertilizers input is sufficient to boost its productivity while requiring very little irrigation. Coupled with various sustainable agricultural techniques, like intercropping and crop rotation, these crops have the potential to maintain the high yields of industrial agriculture while having a minimal ecological impact (Garibaldi *et al.* 2017).

Intercropping is the practice of growing two or more crops together. It ensures some harvest in the event of one crop failing due to adverse weather conditions. Many orphan crops have shown to benefit in terms of yield and other factors when intercropped with other crops. Quinoa intercropping with corn, beans and tarwi improved quinoa yield and helped in pest control (Rasmussen *et al.* 2003). Broomcorn millet, when used in crop rotation with other crops, helps in weed control, prevention of diseases/pests, and helps in maintaining soil moisture (Habiyaremye *et al.* 2017). Thus, it can be beneficial to promote orphan crops among farmers to achieve agricultural sustainability in the long-term.

5.2 *Genetic resource for crop improvement*

Orphan crops have evolved naturally to the stressful conditions of the harsh environments where they grow. These crops provide us with readymade solutions to improve the stress tolerance of the major crops which are being grown globally. Advancements in various omics techniques have made it possible to investigate the mechanisms responsible for the stress resilience of these orphan crops. Any success in the identification of genes or signalling mechanisms responsible for stress tolerance can be a big boost in our efforts to improve the stress tolerance of major crops.

5.3 *Diversity in the human diet*

Global lifestyle is becoming fast-paced, and as a result, the food habits are also shifting rapidly. While the developed countries have traditionally consumed more animal-based diets, including meat and dairy products, developing countries are still heavily dependent on plants for their food (Khoury *et al.* 2014). While globalization has improved the quality and quantity of food available, it has reduced the availability of minor foods which added diversity to our diets. Many of the developing countries are shifting towards Western diets, which are mostly carbohydrate-rich and are responsible for many chronic diseases (Cordain *et al.* 2005). Malnutrition, obesity and diabetes have become a global pandemic due to the consumption of these carbohydrate-rich diets (Popkin *et al.* 2012). Research has shown that a properly balanced diet can help prevent many of the modern diseases, including cancer (Martinez-Outschoorn *et al.* 2017; Maddocks *et al.* 2017). This has resulted in a gradual shift in the food habits towards healthier food options.

Orphan crops are the perfect solution to diversify the human diet. Besides, these crops fulfil the major requirements for healthy food vis-a-vis animal-based foods. They are low in carbohydrates, high in fibre content and rich in proteins and minerals (Saleh *et al.* 2013; Nowak *et al.* 2016). Besides, these crops are rich in many secondary metabolites with antioxidant properties that are beneficial for the human body (Saleh *et al.* 2013; Nowak *et al.* 2016). These foods can be proven to be very healthy in the long-term, and prevent diet-related pandemics.

6. Development of orphan crops

Some of the orphan crops are still not domesticated and have a lot of potential for improvement in terms of quality and quantity of yield (figure 1). Lessons learned through the domestication of various crops in the past can serve as a guide and lead to faster improvement of these crops. Besides, the latest developing techniques, such as high-throughput sequencing and genome-editing, can play a crucial role in the genetic improvement of these minor crops.

Since the orphan crops are already comparatively more stress tolerant and nutritious, domestication efforts must be focussed mainly on boosting the yield. Many of the orphan crops are evolutionary close to some of the major crops. Genes controlling characters like grain size, grain weight and number, and height, are often conserved, and hence, these can be directly targeted using the advanced genome-editing techniques, like CRISPR/Cas. The genome of these crops should be sequenced and made available publicly to allow large-scale work on these crops. This will serve as a solid foundation for the improvement of these crops through various techniques, including molecular breeding and genome editing.

7. Challenges for orphan crops

Most of the orphan crops have minimal documented literature. Besides, most of the crops are restricted to their country of origin and are facing the threat of extinction. Hence, it is imperative to preserve such crops by all means possible. African Orphan Crops Consortium (AOCC) has selected 101 orphan crops for detailed studies and whole-genome sequencing. Similarly, various institutes all around the world have taken up different crops for detailed analyses, and many such crops already have their genome sequenced (Tadele 2019). There are initiatives dedicated to the research and development of orphan crops, such as AOCC and Crops for the Future.

The germplasm of orphan crops needs to be collected and deposited in seed vaults to prevent the loss of genetic diversity due to natural or human-made disasters. Apart from the cultivated varieties of orphan crops, efforts should be made to document and

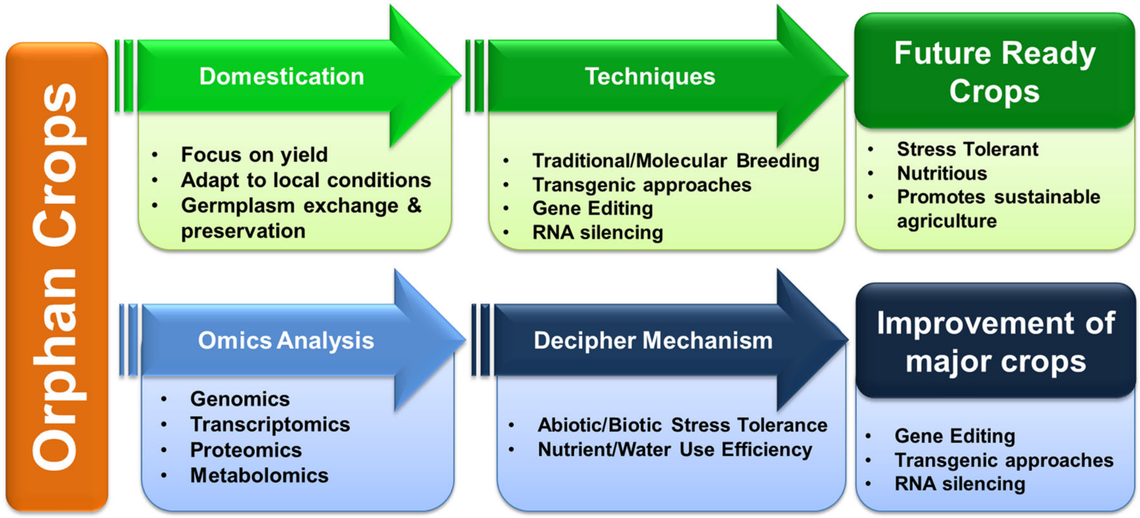

Figure 1. Development of orphan crops. Domestication of orphan crops via different breeding and biotechnological techniques with focus on yield will lead to the development of future-ready crops. Further, research on the various aspects of stress tolerance mechanism using the omics approaches will help in the improvement of stress tolerance capacity of major crops.

preserve even the wild relatives to provide genetic diversity required for improvement of these crops.

State support for limited crops, most of which are water-intensive, has forced farmers to grow these crops in water-scarce regions, instead of the ecologically more appropriate crops such as millets and pulses. The 'Punjab Water Syndrome' is the result of such a flawed state policy (Kulkarni and Shah 2013). Hence, policy changes are required to promote the cultivation of these orphan crops. Awareness campaigns must be launched to help in the adoption of these orphan crops by the farming community.

8. Conclusions

The Green Revolution was a turning point in the history of agriculture. It introduced many advancements which ensured food security around the world. However, climate change and the increasing world population have posed new problems, which need to be solved immediately to ensure future food security. Orphan crops present a unique opportunity with many points to their credit. Besides being highly nutritious and stress tolerant, these crops offer various advantages when intercropped with other crops. They can easily fulfil the demands of the modern generation, which now prefers a low-carbohydrate and nutrient-rich diet. Hence, it is imperative to integrate orphan crops into current agricultural practices and usher another revolution to make agriculture more sustainable for global food security.

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