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Contribution of induced mutation in crops to global food security

Fatma Sarsu[1], Isaac Kofi Bimpong[1] and Ljupcho Jankuloski[1]

[1]Plant Breeding and Genetics Section, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency, Vienna, Austria.
Corresponding author, e-mail: F.Sarsu@iaea.org

Contribución de la mutación inducida en cultivos a la seguridad alimentaria mundial

Abstract

Mutation breeding for crop improvement is a technique used for over 70 years. Induced mutation is a fast way to increase the rate of spontaneous genetic variation in plants contributing to global food security. The genetic variability, created through mutagenesis i.e. physical or chemical, is an important breeding material for developing improved varieties and many studies in the field of functional genomics. The randomly generated heritable genetic changes are expressed in the mutant plants, which are selected for new and useful traits, such as high yielding, disease resistance, tolerance to abiotic stresses and improved nutritional quality. The technique helps to improve the tolerance of crop species to adverse climatic conditions, such as extremes of temperatures, drought, occurrence of pests and diseases. Through support provided by the Joint FAO/IAEA Division, significant agronomic and economic impact has been generated in many countries. The FAO/IAEA Mutant Variety Database (MVD) (http://mvd.iaea.org) demonstrates the significance of mutation induction as an efficient tool in crop improvement. The extensive use of induced mutant germplasms in crop improvement programs resulted in releasing of more than 3,332 mutant varieties from around 228 crop species (20 July 2020).

Keywords: Crop improvement, Food security, Induced mutations, Mutant varieties, Plant breeding.

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Resumen

El mejoramiento por mutaciones para la mejora de cultivos es una técnica utilizada desde hace más de 70 años. La mutación inducida es una forma rápida de aumentar la tasa de variación genética espontánea en plantas que contribuyen a la seguridad alimentaria mundial. La variabilidad genética, creada a través de mutagénesis, es decir, física o química, es un material de reproducción importante para el desarrollo de variedades mejoradas y muchos estudios en el campo de la genómica funcional. Los cambios genéticos hereditarios generados aleatoriamente se expresan en las plantas mutantes, que se seleccionan por características nuevas y útiles, tales como alto rendimiento, resistencia a enfermedades, tolerancia al estrés abiótico y mejor calidad nutricional. La técnica ayuda a mejorar la tolerancia de las especies de cultivos a condiciones climáticas adversas, como temperaturas extremas, sequía, aparición de plagas y enfermedades. Gracias al apoyo proporcionado por la División Mixta FAO / OIEA, se han generado importantes efectos agronómicos y económicos en muchos países. La base de datos de variedades mutantes (MDV, por sus siglas en inglés) de la FAO / OIEA (http://mvd.iaea.org) demuestra la importancia de la inducción de mutaciones como una herramienta eficaz en la mejora de cultivos. El uso extensivo de germoplasmas mutantes inducidos en programas de mejora de cultivos dio como resultado la liberación de más de 3332 variedades mutantes de alrededor de 228 especies de cultivos (20 de julio de 2020).

Palabras clave: Mejoramiento de cultivos, Mutaciones inducidas, Seguridad alimentaria, Variedades mutantes.

INTRODUCTION

Food security, nutrition and promotion of sustainable agriculture are the key issues on the national governments' agenda in many countries. According to projections, the expected total population growth will be more than nine billion by 2050; therefore, an increase of at least 70% in food production is essential in the next three decades [1, 2]. The available land for agricultural expansion is very limited, thereby breeding new improved varieties with adaptability to climate change environment and improvement of crop productivity is becoming ever more important.

The impact of mutation breeding in plant development of crop production and providing sustainable agriculture is well known worldwide [3]. Mutation, which is heritable change in the genetic material of a living organism can lead to the creation of new germplasms which can be subsequently selected for better traits such as yield, resistance to disease pest, tolerance to abiotic stresses, nutritional quality, growth habits, and preferred end-user characters [4].

Climate change is largely accepted as a factual and pressing global problem. Nuclear techniques in plant mutation breeding has an important role in plant adaptation to climate change. Through global warming and the more frequent occurrence of extreme weather, it is an essential and effective measure to apply the good varieties with biotic/abiotic stress tolerance. The technique helps to enhance tolerance of crop species to adverse climatic conditions, such as high temperatures, drought, and occurrence of pests and diseases [5, 6].

Mutation breeding has become a traditional method in plant breeding and has contributed to the present germplasm and development of new varieties with desired traits. Based on the FAO/IAEA Mutant Variety Database [7] on the officially registered mutants, a total of 3332 mutant crop varieties in 228 crop species, across 73 countries have been released for planting in numerous countries throughout the world (Figure 1a-b). The mutant varieties are improved for a different trait such as resistance to biotic stress (557), tolerance to abiotic stress (248), increased yield and yield components (1029), quality and nutrition traits (1173), and agronomic and botanic traits (2981).

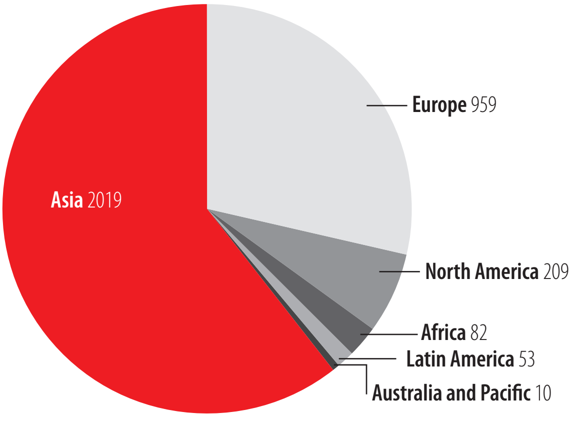

Figure 1a) The number of registered mutant varieties in different continents (July 2020, The FAO/IAEA MVD).

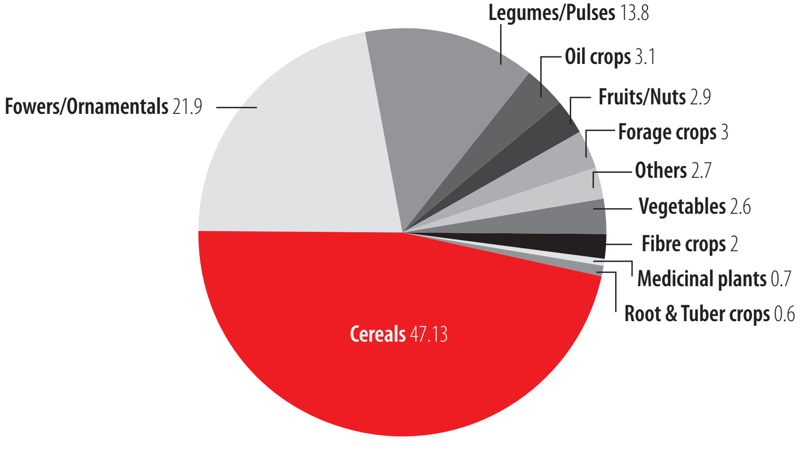

Figure 1b) Proportion of different mutant plant varieties (July 2020, The FAO/IAEA MVD).

The released plant mutant varieties are mostly consisted of cereal species (47.13%) with the majority of (25%) rice (Figure 1b), flowers/ornamentals (21.9%) and legumes and pulses (13.8%). Most of the mutant varieties are released in Asia (2019), following by Europe (959), North America (209), Africa (82), Latin America (53) and Australia and Pacific (10) (Figure 1a).

Numerous papers have already been available on the impact of mutant and mutation-derived crops [8,9], and many papers were presented at the Joint FAO/IAEA International Symposium on "Plant Mutation Breeding and Biotechnology" in 2018, in Vienna, Austria, and at the Symposium on "Applications of Nuclear Techniques in Agriculture" in 2020, in Quito, Ecuador. The worldwide contribution of induced mutations for food production and the food security is presented in this paper.

CONTRIBUTION OF INDUCED MUTATIONS TO THE GLOBAL FOOD SECURITY

Asia

Asia has more than 60% of induced mutations and mutation-derived varieties. China, Japan and India are countries that have registered the vast number of mutant varieties with an economic impact on food security.

In China, mutation induction in crops has been one of the efficient breeding approaches for more than 50 years. Based on the FAO/IAEA Mutant Variety Database (https://mvd.iaea.org/), China has released over 800 mutant cultivars in different crops which includes 46 ornamental species. The maximum annual dissemination area of mutant varieties is more than nine million hectares; which results in production of over 1.5 million tons of crops annually, with an estimated value of about US$ 500 million [10].

Numerous research institutions and universities involved in mutation breeding in India. Thus far, over 340 mutant varieties have been registered in different crops such as 56 legumes and pulses, 32 edible oil plants and 26 groundnut mutant varieties. Appealing traits for released mutant includes high-yielding, early-maturing, large seed, high oil content and tolerance to biotic and abiotic stresses. The first induced large seed groundnut mutant variety, 'TG 1', was developed using X-ray irradiation in 1973. Subsequently, 15 Trombay groundnut (TG) varieties with superior traits, such as high-yield, large seed, early maturity were developed. Forty-five percent of Indian breeders' groundnut seeds are TAG varieties, mostly TAG24. Based on breeder seed statistics, these groundnut varieties produced 1 022 metric tons worth US$ 1.18 million from 1998 to 2008 [8, 11].

In Japan, the research on radiation-induced mutation started during the 1960s. In total, 479 mutant varieties have been registered comprising 79 species, improved using X-and gamma- rays, ion beams, chemical mutagenesis and *in vitro* culture (soma clonal variation), and approximately 79% of these were induced using gamma irradiation [12].

Pakistan has succeeded to develop 59 mutant varieties in different crops, such as cotton (12), mung bean (11), rice (10), chickpea (9), wheat (6), lentil (3) oilseed brassica (3), mustard (1), sesame (2), groundnut (1), castor bean (1), and mandarin (1). The mutant variety 'NIAB 78' was the first cotton variety developed in 1983 using induced mutations. It has assisted transformation of cotton production and stimulated a wider impact on agriculture in Pakistan. 'NIAB 78' had early maturity and higher yield and showed wider adaptability and eventually covered 80% of the cotton area in Punjab and Sindh provinces [8]. By introduction of this variety, cotton production increased from 654 000 tons to 2 613 000 tons during 1991 and 1992 [13]. This mutant variety remained in farmers' fields over a very long period (1983–2000) and led to an increase in cotton production from 1 024 000 tons to 72 766 000 tons per year in Pakistan [14].

Mutation breeding for crop improvement, particularly in rice and soybean, is one of the most successful field of application of nuclear techniques in Viet Nam. To date, 58 crop varieties predominantly rice (36) have been released to farmers. The rest include, soybean, chrysanthemum, maize, groundnut, Indian jujube and field mint making significant contributions to national food security [7]. Rice which represents more than 60% of mutant varieties, does not only contribute to the national food security, but also provides income and decreases poverty among millions of rural communities in Viet Nam. These rice mutant varieties have 10–20% higher yields in comparison to the parent varieties, with lodging resistance, tolerance to acid soils, salinity, tolerance to biotic stress, short duration and better nutritional quality. Due to short duration, mutant rice varieties can be cultivated 2–3 crops per year and avoid early flooding. With resistance to diseases and pests, cultivation can be done with a reduced number of sprayings, which saves costs and protects the environment from excessive use of pesticide [8- 9].

Europe

Basic mutation research commenced in Europe during the late 1920s. Mutation breeding has become a significant method in the European plant breeding programmes resulting release of 959 mutant varieties, particularly in wheat and barley [15,16].

In Bulgaria, mutagenesis has been efficiently applied in crop breeding for over 50 years. The country has released 76 mutant cultivars in 15 different crop species, such as barley (5), wheat (5), durum wheat (9), maize (26), sunflower (3), lentil (4), bean (2), pea (1), chickpea and vetch (2), soybean (5), tomato (6), pepper (4), cotton (2), and tobacco (2). Some of the mutant varieties, e.g. maize mutant hybrid 'Kneja 509' and durum wheat variety 'Gergana' have become the leading varieties occupying up to 50% of the planting area from 1984 to 2000. In durum wheat, mutant varieties have not only covered nearly all the growing areas but also doubled the yield over the past 30 years [17].

Wheat mutation breeding programme had a great success with officially released eleven durum wheat (*Triticum turgidum* ssp. Durum) varieties in Italy. Six of them were developed through the direct use of identified mutants and five were developed through cross breeding. Creso is one of the best durum wheat varieties which was released in 1974 that has a significant impact in Italian economy contributing with US$1.9 billion. Many wheat mutant lines developed in Italy were used in the wheat improvement programs in Austria and Bulgaria for releasing improved wheat varieties [18, 8].

North America

The United States has developed 139 mutant varieties including the first semi-dwarf rice variety, 'Calrose 76' which was induced by gamma irradiation and officially released in 1977 in California. This gene is transferred by crossing other varieties and led to the development of 22 new rice cultivars in the United States, Australia and Egypt [19].

Latin America

The IAEA, through its technical cooperation program, together with the Food and Agriculture Organization of the United Nations (FAO) has been working with countries in Latin America and the Caribbean for many years to introduce and strengthen crop mutation breeding. In 2014, a new project was launched, with the participation of national agricultural research institutes and universities from 18 countries in the region. The Joint FAO/IAEA Division contributed extensively to human capacity building through regional training courses (organized twice a year) on plant mutation breeding techniques for crop improvement, contributing towards food security. The project used mutation breeding techniques to develop improved crops with better tolerance to environmental stresses and better quality. The project targeted crops of economic interest to the region, as well as native crops of more local importance. The improved plants are being developed into new varieties that can be disseminated to farmers, where they will have an impact on food security and the agricultural economy in the region. As a result of the project, participating countries have successfully developed a range of new mutant varieties.

In Argentina, rice varieties from Instituto Nacional de Technologia Agropecuaria (INTA) covered 40% of the rice production area during 2016-17 [20]. Additionally, they were distributed in other Latin American countries, such as Uruguay, Colombia, Chile, Costa Rica, Panama, Dominican Republic, Nicaragua and Honduras, where weedy red rice is a problem. Currently Imidazoline herbicide resistant varieties are grown on more than 800 000 hectares. The IMI tolerant rice varieties have increased production and excellent growth. They have also been very useful to improve abandoned rice fields for being severely occupied by red rice [20].

Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI) successful example from Brazil, has been effectively using induced mutations with the collaborating Centre of Nuclear Energy in Agriculture (CENA/USP) in the improvement of new rice varieties. In 2013, the mutant rice variety, 'SCS118 Marques', was developed through gamma application of parent SCSBRS Tio Taka variety [7]. This variety has lodging resistance, showing moderate resistance to blast disease, high yield, late maturity, long grains and consumer preferred cooking quality and is advised to be used in rice-producing areas of Santa Catarina. The mutant variety 'SCS121 CL' which shows resistance to Kifix (an herbicide of the Imidazolinones group) was released in 2014. It enables better control of weedy rice in the fields with the application of the herbicide, dropping the use of other chemicals [21,7].

The IMI-herbicide resistant cultivar (Clearfield rice) was improved through mutagenesis without the addition of any foreign gene and was registered in 2002 [22]. That has provided the selective control of weedy and wild rice in the fields. Additionally, employment of combined management practices has increased rice yield in Brazil by approximately 2500 kg ha^{-1}, an increase of 50% [23]. Around 1.1 million ha of an arable land was planted in Brazil with IMI herbicide resistant variety [24].

Induced mutation has been successfully applied in Cuba for genetic improvement of crops. Numerous successes have been achieved in a range of food and ornamental crops. So far, Cuba has released 21 varieties in hibiscus (3), sugarcane (4), tomato (3), rice (9) and soybean (2) [7]. The rice variety 'LP7', officially released in 1997, has higher yield and is tolerant to salinity. Another success is in tomato, 'Maybel' and 'Domi' mutant varieties, have significantly increased yields under drought conditions [25, 26].

Since 1978, Peru has continuously used induced mutation in crop improvement programs and produced significant results. The barley mutant variety 'UNA La Molina 95' was released in 1995 and is characterized by its earliness, short stature, and production of naked grains (huskless) with higher protein content [7]. The high yielding and better-quality barley variety 'Centenario', was released in 2006. It is grown at altitudes of up to

5 000 m above sea level and is changing the local varieties in the Central Highlands of Peru, extending the range of crops to higher altitudes [7,27]. The amaranth mutant variety 'Centenario' released in 2006, is cultivated in the Peruvian highlands, and can be labelled as an "organic product" and exported as a high-value commodity [7, 28].

Africa

The semi-dwarf mutant rice varieties, 'Giza 176' and 'Sakha 101', were released in Egypt during the 1990s with the standard yield abruptly increasing from 3.8 t ha^{-1} to 8.9 t ha^{-1}. 'Giza 196' is cultivated as the lead variety with a yield of 10 t ha^{-1} [9]. Induced mutation technique was also successfully applied in edible oil crops, such as sesame and safflower. Five sesame varieties were developed with high yield and good quality during 1992 to1996. Two safflower varieties were released in 2011 with high yield and oleic fatty acid, resistant to leaf spot and smut, contributing to higher income for farmers in the country [7].

Since 1983, Ghana Atomic Energy Commission has been working on induced mutation in crop improvement. Cassava mutant variety 'Tekbankye' with excellent cooking and pounding quality was released in 1997. This mutant variety is tolerant to Africa Cassava Mosaic Virus (ACMV), thereby leading to its quick adoption by many farmers in Ghana's forest zone as it is used to prepare *fufu,* the nation's most popular cassava-based food. Farmers continued to cultivate this mutant variety in large acreages until its resistance to mosaic virus disease, particularly ACMV, broke down in the early 2000s. However, due to its preferred taste by consumers it is still being grown by some farmers for domestic consumption [9].

Namibia's Ministry of Agriculture, Water and Forestry developed four sorghum and seven cowpea varieties with 10–20% higher yield than local cultivars under drought conditions and pre-released to farmers. The new developed improved mutant varieties will be disseminated to more than 8000 farmers. Farmers are expected to be involved in seed multiplication, and therefore number of farmers and production area to be subsequently increased in the next years. The Ministry of Agriculture is facilitating seed multiplication for the 2020 and 2021-22 cropping seasons and planning to provide all potential cowpea growers in the country during the 2023 cropping season [29, 30].

Mauritius has released three high-yielding mutant varieties, namely Summer King, Summer Star and Rising Star. These varieties were distributed among farmers and seed multiplication continues to reach more farmers [7].

In the early 1990s, Sudan began to integrate mutation breeding methods for crop improvement. Successful breeding programs using nuclear techniques and plant biotechnologies were conducted to enhance productivity of cereals crops, banana, tomato and groundnuts under stress environment to ensure sustainable food security and well-being of farmers. The outcome of these efforts resulted in development of a banana variety 'Albeely' with high yield potential. 'Albeely' is widely cultivated by farmers in banana production areas along the Blue Nile in the south of Wad Medani [9]. A drought-tolerant peanut variety, 'Tafra-1', was released in 2018 for Sudanese farmers in drought-prone areas, which improved their livelihoods and led to an increase in the country's' exports [7,31].

CONCLUSIONS

Enhancing food security and availability of enough food is among the top priorities for most of the developing countries. The extensive application of mutagenesis in crop breeding programs all over the world has assisted the official registration of over 3 300 mutant varieties during the last 85 years. A large majority of released mutant varieties (including cereals, pulses, oil, root and tuber crops, and ornamentals) have been released in developing countries, resulting in positive economic impacts. Thus, plant mutation breeding is an efficient tool for preserving and enhancing global food security. Some highlights were presented in this paper showing that many mutant varieties are covered in Asia, Europe, Latin America and Africa. For example, in Peru, farming activities 3000 meters above sea level are very limited by the harsh conditions of the environment. The Cereal and Native Grains Research Program produced improved mutant barley and amaranth varieties thriving at up to 5000 m altitude, consequently providing Andean local farmers with more food, income and enhancing their quality of life. The mutant barley variety, Centenario II, occupies 18% of the dedicated barley growing area in Peru, through this, 15000 farmers profited from the release of this barley variety. Vietnams' mutation breeding program resulted in the releasing of several rice and soybean varieties contributing to national socio-economic impact. More than 4 million farmers in Vietnam are using rice varieties developed through mutation breeding. The success in soybean breeding is documented with occupation of 50% of the soybean area in Vietnam.

The Joint FAO-IAEA Division of Nuclear Techniques in Food and Agriculture has advanced the research, improvement and application of nuclear techniques in food and agriculture for the past 55 years. The success in the area shows the achievement of the Joint FAO-IAEA Division and the essential support given to the Member States. In the last decade, induced mutation has combined current biotechnologies, such as the use of doubled haploid technology, and application of molecular markers, which offers the breed of new varieties within a short space of time. Mutation breeding in combination with other technologies provides the fastest way to generate genetic diversity to develop suitable crops and their cultivars that can withstand all adverse stresses as a result of climate change and to ensure food security globally.

AUTHOR CONTRIBUTION

Fatma Sarsu formal analyses, investigation, visualization, writing original draft- review and editing; Isaac Kofi Bimpong and Mr Ljupcho Jankuloski revised the article critically and contributed to the write up.

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