The contribution of innovative nuclear technology to sustainable agriculture development

Case study

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SUMMARY

Nuclear science and technologies are part of the cutting-edge research and development efforts that are accelerating globally to develop and implement sustainable, climate-smart agricultural practices. Bangladesh, one of the most densely populated countries in the world and one of the most vulnerable to the impacts of climate change, is using nuclear technology to increase the quality and productivity of its crops. The objectives of this case study are to

a) draw lessons learned from Bangladesh's success
b) examine the benefits of nuclear technologies used for plant mutation breeding and how the use and access to these technologies can be sustained, and
c) demonstrate the important role of the IAEA in making these technologies available and supporting their safe, secure and sustainable use by its Member States.

INTRODUCTION

The world's population is projected to reach 9.1 billion by 2050. The Food and Agriculture Organization of the United Nations (FAO) estimates that global food production (net of food used for biofuels) would have to increase by 70 percent to match this growth.[1] To this end we would need to increase land productivity and conserve natural resources in the face of a multitude of severe challenges: climate change, increased droughts, flooding and rising sea levels which hamper crop productivity and make farming a high-risk venture.[2]

Nuclear science and technologies are part of the cutting-edge research and development efforts that are accelerating globally to develop and implement sustainable, climate-smart agricultural practices. These technologies not only increase agriculture productivity, food security and nutritional quality but also improve the livelihood of farmers. Importantly these technologies benefit instead of deplete the natural resources base that sustain these agricultural practices. The FAO and the International Atomic Energy Agency (IAEA) established a join division which has, since 1964, been a global leader in the application of irradiation for plant mutation breeding and crop improvement.[3]

This case study examines nuclear technologies that improve the quality and the productivity of crops through plant mutation breeding (mutagenesis) in Bangladesh. The country faces some of the greatest challenges in terms of population growth and density and is considered one of the most vulnerable countries to the impacts of climate change.[4] The Bangladesh Institute of Nuclear Agriculture (BINA) has been using nuclear technology to improve crops for the last 50 years. Nuclear science and technologies have been credited with tripling the country's rice production, a staple food in Bangladesh.[5] This study will show that mutation breeding with nuclear technologies is making an essential contribution to food security and to ending hunger in Bangladesh and has the potential of making a contribution to improving global crop production. The role of the Joint FAO/IAEA Division in developing and transferring these technologies will be examined. Other aspects contributing to Bangladesh's success will also be discussed, such as regional cooperation and national policy frameworks.

1 How to feed the world by 2050. Available at: http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

2 Manual on Mutation Breeding, Third Edition Edited by Spencer-Lopes, M.M. Forster, B.P. and Jankuloski, L. Plant Breeding and Genetics Subprogramme Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture Vienna, Vienna, 2018

3 Ibid.

4 Climate Change Profile: Bangladesh Ministry of Foreign Affairs of the Netherlands, 2018. Available at: https://www.government.nl/documents/publications/2019/02/05/climate-change-profiles

5 Bangladesh triples rice production with help of nuclear science by Nicole Jawerth, IAEA Bulletin, June 2017. Available at: https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull58-2/5821415.pdf.

Gamma radiation or isotopic radiation sources are commonly used for plant mutation breeding. However, there are safety and security risks associated with the use, transportation, storage and disposal of these sources. This case study highlights these security risks and touches upon the support provided by the IAEA to its Member States to manage the risks. Non-isotopic alternatives, such as X-ray and ion beam irradiation, could be suitable alternatives to gamma irradiation and have none of the security concerns related to gamma irradiation. However, challenges remain regarding the efficiency and cost effectiveness of the technologies, especially when used in developing countries. The study proposes steps that can be taken by the IAEA and its Member States to ensure the continued access to and use of nuclear technologies by all countries.

PLANT MUTATION BREEDING IN BANGLADESH

Dr Md. Abul Kalam Azad worked in the plant breeding division of BINA for 26 years. When asked whether he felt that he had contributed to food security and poverty reduction in Bangladesh and his answer was a resounding "yes".[6]

Dr Azad in the the 'Monga' affected area in Rangpur during the harvest of iron and zinc rich paddy variety Binadhan-20, one of the mutant varieties he developed. Captured during an interview with a TV channel.

Over the course of his career Dr Azad developed five different varieties of rice, with plant mutation breeding using nuclear techniques that have changed the lives of millions of Bangladeshis. He has also developed different varieties of peanuts, jute, onions, and wheat. This he has done with the support of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, as well as Bangladesh's regional partners.

To understand the significance of his work one needs look no further than the 170 million people in Bangladesh, most of whom are subsistence farmers depending on rice as a source of food, to feed their cattle and as a source of income. Rice alone constitutes more than 90 percent of the total food grains produced annually in the country.[7] In the eighth most populous country in the world, which is half the size of the United Kingdom, food security and economic growth depends on the ability of farmers to enhance crop yield as much as possible. Bangladesh faces the duel challenge of low yielding crops and declining agricultural land area. According to the World Development Indicators,

6 A series of interviews were conducted with Dr. Md. Abul Kalam Azad, previously the chief scientific officer, now the Director (Administration and Support Service), Bangladesh Institute of Nuclear Agriculture (BINA) during which he graciously shared his knowledge and experience on plant mutation breeding.

7 Government input support on Aus rice production in Bangladesh: impact on farmers' food security and poverty situation by Md. Taj Uddin & Aurup Ratan Dhar. Avaiable at: https://agricultureandfoodsecurity.biomedcentral.com/articles/10.1186/s40066-018-0167-3

Farmer in Bangladesh
preparing to harvest rice

Photo: Nicole Jawerth/IAEA

arable land as a percentage of the total land area has decreased from 64.5 percent in 1995 to 59.7 percent in 2015. This fact in combination with rapid population growth, poses a considerable threat to food security for the country.[8]

Dr Azad explains that in the northern region of Bangladesh (particularly the greater Rangpur district) from mid-September to mid-December, there used to be no harvests and, as a result, no work. Ten percent of Bangladeshis live in this region and used to suffer from acute deprivation and starvation during these months. In Bengali this food and animal fodder famine is known as the "Monga". Binadhan-7, a rice variety developed by BINA, with a shorter growing time and a higher yield than traditional northern varieties, brought an end to the "Monga". Farmers are now able to harvest three crops instead of two during the harvest season as the crop matures in 115 days instead of the usual 150 days, allowing 30 to 35 extra days to grow other crops and vegetables. The shorter crop cycle also decreased the crop's vulnerability to terminal drought and disease. This variety produces up to four tons of rice per hectare while the traditional varieties produce only two tons. Subsistence farmers can put food on the table throughout the year and are also able to sell their rice and increase their income. Binadhan-7 has also ended the cattle feed crisis as the rice plants are used to feed the cattle after the harvest.

Bangladesh rice market

Photo: Nicole Jawerth/IAEA

8 WB (World Bank). World Bank Open Data. 2018. Available at: https://data.worldbank.org

The north-western region of Bangladesh, which is considered as the food bowl of the country, is experiencing longer and more severe droughts and high temperatures as a result of climate change, which pose a significant threat to rice production. Boro varieties are the most popular rice varieties in this region. Farmers plant these varieties during the Boro season, from January to April, which is a dry season and the rice is therefore heavily dependent on irrigation, which is costly and depletes the groundwater. To provide farmers with more sustainable options Dr Azad developed Binadhan-14. Binadhan-14 is a Boro rice that can withstand temperatures of up to 38°C (100.4°F) during anthesis (flowering), is photoperiod insensitive and lodging resistant.[9] The recommended planting time for Boro rice is between December and January, but these traits allow this variety to be planted as late as the last week of March. Another trait is short duration which means it takes only 100 to 110 days to mature as compared against 140 to 160 days in other varieties, allowing for more crops to be planted in one season.

Another planting season is the Aus season, from March to July, when most of the rainfall occurs. However the rice varieties planted in this season, whilst requiring less water, are low yielding and not popular with consumers. To encourage farmers to plant more rice during the Aus season, Dr Azad mutated Aus rice into a high-yielding, short duration, drought and heat tolerant, short plant with a higher harvest index known as Binadhan-19. A short plant is wind resistant and a higher harvest index means the plant is more efficient at producing seeds. The rice was also developed with a golden coloured long fine grain, which is popular among consumers. All these traits combined are convincing farmers to plant more rice during the Aus season and BINA has distributed almost 100 tons of seeds since the introduction of this Aus rice variety in 2017. As a result, farmers' dependence on underground water for irrigation is being reduced while rice production is increasing.

Nuclear techniques have been credited with tripling Bangladesh's rice production.[10] According to the World Agricultural Production Report of US Department of Agriculture (USDA), Bangladesh is expected to produce 36 million metric tons of rice in 2020/2021 making it the third largest producer in the world after China and India.[11]

New rice varieties, such as Binadahn-7 and Binadhan-14, developed by scientists at the Bangladesh Institute of Nuclear Agriculture (BINA)

Photo: Nicole Jawerth/IAEA

9 Lodging resistant mean that the plant is not affected by heavy wind and photoperiod insensitive means that the rice flowers under both short- and long-day conditions..

10 Bangladesh triples rice production with help of nuclear science by Nicole Jawerth, IAEA Bulletin, June 2017 Available at: https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull58-2/5821415.pdf

11 United States Department of Agriculture Foreign Agricultural Service Circular Series WAP 8-20, August 2020 Available at: https://apps.fas.usda.gov/psdonline/circulars/production.pdf

PLANT MUTATION BREEDING EXPLAINED

Plant breeding is as old as human civilization and the dawn of agriculture. Beginning with the domestication of wild species approximately 10,000 years ago, plant evolution was manipulated by human's conscious selection of plant types that were productive and useful for humans and their livestock. During the past 100 years, advances in science have allowed us to effectively speed up the process of evolution and target complex genetic traits, thereby contributing to superior cultivars. These traits include yield, tolerance to drought and to acid soils, disease resistance and crop quality.[12]

Following the discovery of X-rays, radioactivity and radioactive elements at the end of the 19th century, it was demonstrated that radiation caused mutations in fruit flies and in crop plants. The discovery that mutations could be induced at will led to a rapid and widespread adoption of induced mutations as a crop improvement tool. The establishment of the IAEA in 1957 provided the greatest impetus for induced mutation breeding in keeping with its slogan of "Atoms for Peace." In 1964, the FAO, which is a United Nations specialised agency with the mandate to eradicate hunger and malnutrition, joined forces with the IAEA to establish the Joint FAO/IAEA Division. The organisations set out together to help their Member States use nuclear non-power applications to produce more, better, and safer food.[13]

Shoba Sivasankar, Section Head for Plant Breeding and Genetics in the Joint FAO/IAEA Division, explains the process of plant mutation breeding using nuclear technology as the exposure to radiation of seeds or other plant materials.[14] The radiation accelerates the natural process of spontaneous mutation and produces novel changes in the plant's genetic structure. The seeds are then planted, and the plants scanned for specific traits. Selecting the traits requires precision and is time-consuming as one needs to be sure that the trait you find is the one you are looking for, such as resistance to a disease that is plaguing that variety, drought resistance or tolerance to high levels of salt in the soil. The plants that exhibit the trait are then further developed into new varieties that can be cultivated by farmers.

Dr. Sivasankar noted that gamma radiation is commonly used for plant mutagenesis as it has been accessible and the most studied method to create mutations through

Joint FAO/IAEA Plant Breeding and Genetics Laboratory. Seibersdorf, Austria

Photo: Dean Calma / IAEA

An IAEA scientist with two interns at the Seibersdorf Plant Breeding Unit checking on banana plants

Photo: Dean Calma / IAEA

12 Crop Breeding and Applied Biotechnology: Evolution of plant breeding. Arnel R Hallauer. Available at: https://doi.org/10.1590/S1984-70332011000300001

13 Manual on Mutation Breeding, Third Edition Edited by Spencer-Lopes, M.M. Forster, B.P. and Jankuloski, L. Plant Breeding and Genetics Subprogramme Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture Vienna, Vienna, 2018.

14 Interview with Ms Shoba Sivasankar Section Head, Plant Breeding and Genetics|, Joint FAO/IAEA Division, Department of Nuclear Sciences and Applications, IAEA.

physical mutagenesis in a wide variety of crops. Developing a new plant variety with this technique takes eight to ten years on average, as with traditional breeding, but the level of novel genetic diversity that is developed allows for faster and higher improvements in traits. The IAEA provides irradiation services for seeds and other plant material, at its nuclear applications laboratories at Seibersdorf in Austria for those Member States that do not have access to radiation equipment. To Member States that have the technology, the IAEA provides technical information on irradiation techniques and screening for specific traits. This support is provided through Coordinated Research Projects (CRPs) and its Technical Cooperation Programme (TC Programme), in the form of technical guidance for research projects and capacity building (e.g. laboratory equipment and training).

There is an FAO/IAEA Mutant Varieties Database (MVD) that is a repository of voluntarily contributed information from countries on released mutant varieties.[15] There are currently 3331 mutant varieties recorded in this database from 270 different crop species from approximately 80 countries. These include physically induced mutant varieties, so to say induced through radiation, as well as chemically induced varieties.[16] Roughly, two thousand of these varieties come from the Asia Pacific. China, Japan, and India have released the largest number of mutant varieties in the world. European countries are the next largest grouping of countries with released mutant varieties.


A laboratory technician at the IAEA's Plant Breeding Unit in Seibersdorf checking on a phial containing a young banana plant.

Photo: Dean Calma / IAEA

15 FAO/IAEA Mutant Varieties Database (MVD). Available at: https://www.iaea.org/resources/databases/mutant-varieties-database

16 "The FAO/IAEA figures for the numbers of mutant varieties are recognised as being a gross under-estimate for a number of reasons which include mutant varieties are not always registered because such information is only collected from publicly available sources (mostly English) or voluntarily provided by breeders who have some connection with the FAO/IAEA programmes". Plant mutation breeding and biotechnology by the Plant Breeding and Genetics Section Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture International Atomic Energy Agency, Vienna, Austria. Published by the FAO, 2011.

BANGLADESH: A SUCCESS STORY

According to Dr Sivasankar, Bangladesh's success with mutation breeding is due to a variety of factors which include cooperation between Bangladesh and countries in the region and the country's experience in the application of nuclear technology in food and agriculture. BINA has had its own laboratory for plant breeding since 1970. The Joint FAO/IAEA Division, in part through the IAEA's TC Programme, has advised and supported BINA's mutation breeding programme since 1972, providing laboratory equipment, training and fellowships for lab personnel. In addition to making the technology available to its Member States, the IAEA also develops internationally recognised safety standards and provides training on the safe application of these technologies. Furthermore, it provides guidance and support on the physical protection and secure management of the radioactive sources used to produce the radiation required.

Dr Sivasankar explained that the IAEA supports countries to work regionally on plant mutation breeding. Bangladesh is part of the Plant Mutation Breeding Network in the Asia-Pacific region. This network allows countries from the region to exchange technology, and also experimental plant materials allowed by existing national policies. Bilateral exchange of experimental materials that are adapted to similar environments in different countries, and their positive adaptation in the receiving country, allow for the faster development of new and improved crop varieties. A plant breeding programme generally requires six years or more for the selection of desirable improved plants, and their development into a variety that farmers can grow. Regional collaboration can reduce risks and increase benefits for individual countries. She noted that the Asia-Pacific region is the most advanced in plant mutation breeding.

Dr Azad explained the benefits of regional cooperation for Bangladesh, echoing the sentiments of Dr Sivasankar. To develop Binadhan-7, BINA received the initial mutated plant material from Vietnam, which was then screened to suit Bangladesh's own requirements. BINA also sent seeds to laboratories in Thailand and Japan for irradiation with a carbon ion beam accelerator which is a type of heavy ion beam irradiator (HIBI). Binadhan-19 and Binadhan-14 were developed with HIBI, which Dr Azad credits with reducing the time required from ten years to four years for developing a new variety from seed to release.

BINA is part of the Ministry of Agriculture, another factor that contributes to Bangladesh's success in plant mutation breeding. In several countries, nuclear research in agriculture is carried out by nuclear agencies that work independently of the country's national agricultural research and extension system. In these countries, says Dr Sivasankar, the opportunity to distribute the seeds through mainstream agriculture is not optimized.

Dr Azad concurs that being part of the Ministry of Agriculture facilitates the development of technology, as well as the release and distribution of new seed varieties. The seeds developed by BINA are distributed to farmers through formal seed systems, including the national agriculture extension services (part of the Ministry of Agriculture), and are provided to farmers directly by BINA. Another benefit of this coordinated approach between policymakers and scientists is that Bangladesh is able to develop its own approaches and solutions to its food, nutrition and climate change challenges.

BINA scientist presenting a new rice variety
Photo: Nicole Jawerth/IAEA

Experimental field at BINA
Photo: Nicole Jawerth/IAEA

NUCLEAR TECHNOLOGIES USED FOR PLANT MUTATION BREEDING

Plant mutagenesis can also be described as a process whereby sudden heritable changes occur in the genetic information of an organism not caused by genetic segregation or genetic recombination, but induced by chemical, physical or biological agents.[17] The term "physical agent" refers to irradiators such as gamma, X-ray, and ion beams that induce physical mutagenesis. While great strides have been made in the use of chemical agents to induce mutations in plants, physical mutagenesis has distinct advantages. Shahryar Kianian at the United States of America (US) Agriculture Research Services (ARS) Cereal Disease Laboratory researches genome mapping and explains that radiation is still the only way to explore the genome for genes that are not yet identified.[18] In other words, radiation enables the discovery of new genetic traits. Another major advantage of using physical mutagenesis compared to chemical mutagenesis is the degree of accuracy and sufficient reproducibility, particularly for gamma rays which have a uniform penetrating power in the tissue.[19]

Genetic modification (GMO) is another way to alter the genetic material of a plant. Such alterations may include the addition of foreign genetic material (transgenesis), or the mutation or deletion of a gene. Biotechnology is widely used in the US to develop transgenic varieties and GMOs are accepted by the public at large. However, GMOs are subject to stringent regulations, especially outside of the US, where they are often banned. In the last decade a variety of new techniques have been developed, based on advances in biotechnology. In July 2018, the Court of Justice of the European Union clarified that organisms from these new gene editing techniques fall within the scope of the EU GMO legislation as well.[20] In comparison physical mutagenesis is not regulated, as it produces novel genetic diversity by accelerating the natural process of spontaneous mutation in the plant's genetic structure.

The following is a brief description of the technologies used for physical mutagenesis and an analysis of their advantages and disadvantages.

17 Principle and application of plant mutagenesis in crop improvement: a review Yusuff Oladosu,Mohd Y. Rafii,Norhani Abdullah,Ghazali Hussin,Asfaliza Ramli,Harun A. Rahim,Gous Miah & Magaji Usman: Journal on Biotechnology & Biotechnological Equipment, 2013. Available at: https://www.tandfonline.com/doi/full/10.1080/13102818.2015.1087333.

18 Interview with Shahryar Kianian, Research Leader at the ARS Cereal Disease Laboratory: US Department of Agriculture

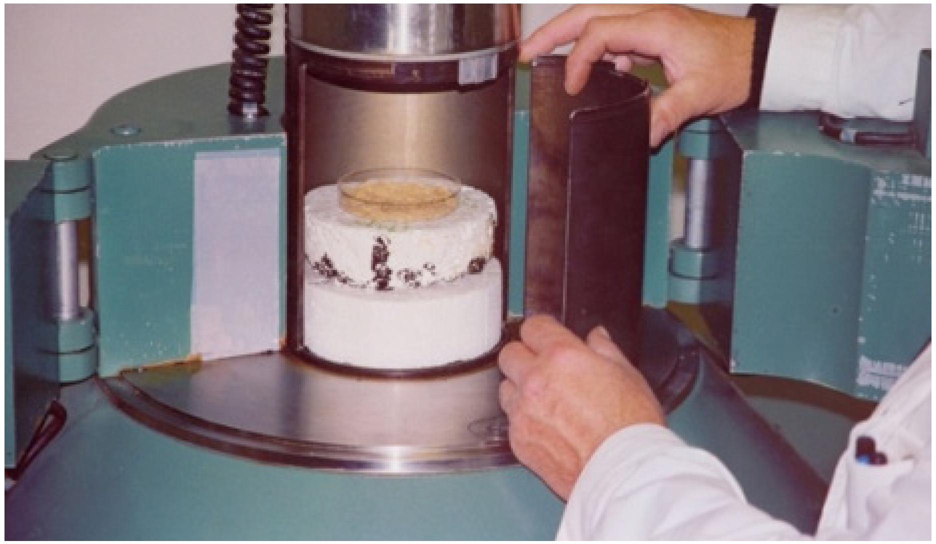
19 Principle and application of plant mutagenesis in crop improvement: a review Yusuff Oladosu, Mohd Y. Rafii,Norhani Abdullah,Ghazali Hussin,Asfaliza Ramli,Harun A. Rahim,Gous Miah & Magaji Usman: Journal on Biotechnology & Biotechnological Equipment, 2013. Available at: https://www.tandfonline.com/doi/full/10.1080/13102818.2015.1087333.

20 European Commission Website: Available at: https://ec.europa.eu/food/plant/gmo/modern_biotech_en\

Gamma radiation

Gamma irradiators are most commonly used for plant mutation breeding. In use since the 1960s gamma irradiators were developed for the cost effectiveness of the radiation process, dose uniformity in product, and operational reliability.[21] The gamma irradiator also has a distinct advantage for prolonged treatments in that it can be used in a greenhouse or in a field in contained conditions so that plants may be exposed at various times and at various developmental stages.[22]

BINA currently has two gamma irradiators which it uses for plant breeding. One Gamma Cell 220 irradiator purchased in 1995 from Canada and one Gamma Chamber 5000 irradiator, purchased from India in 2013. The older irradiator is used to provide low doses of radiation for vegetative propagated crops, callus and pollen irradiation, as the source is almost depleted. The Gamma Chamber 5000 irradiates 90% of the seeds produced at BINA. However, BINA will be looking to purchase a new Gamma Cell 220 by 2023, if not sooner, to replace the Gamma Chamber 5000.



Gamma Cell (Cobalt-60) irradiating seeds at the FA0/IAEA Plant Breeding and Genetic Laboratory IAEA

Photo: IAEA

21 Gamma irradiators for radiation processing, IAEA Brochure. Available at: https://inis.iaea.org/collection/NCLCollectionStore/_Public/37/081/37081743.pdf?r=1

22 Manual on Mutation Breeding, Third Edition Edited by Spencer-Lopes, M.M. Forster, B.P. and Jankuloski, L. Plant Breeding and Genetics Subprogramme Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture Vienna, Vienna, 2018

Security considerations

Gamma irradiators use sources that contain cobalt-60 or cesium-137(Cs-137) isotopes to deliver radiation. Cs-137 is however being phased out globally as this isotope has a half-life of 30 years and reacts readily to form highly mobile water-soluble salts.[23] This means it is easily absorbed into the environment and, in case of dispersal, would leave a large area contaminated for many years. These characteristics make it attractive for terrorists or criminals who could use it in a dirty bomb (radiological dispersal device) or leave it unshielded in a public place (a radiation exposure device). Cobalt-60 has a half-life of 5.2 years. If these gamma sources were to be used for malicious purposes the result would be injury, death and widespread panic, which could ultimately turn public opinion against the use of nuclear technology. The clean-up of the affected area could amount to millions of euros.[24]

The IAEA has developed consensus recommendations, requirements and guidance for the use storage and transport of nuclear and radioactive material, including gamma sources. Standard security measures in irradiation facilities to protect the sources against theft include access control and intrusion detection systems and the IAEA supports physical security upgrades of these facilities upon request. At BINA the room in which the gamma irradiators operate is secured with a magnetic steel door locking system, an IP (internet protocol) based system for monitoring in and outside, a biometric door locking system, alarm and 24-hour security.

Safe and secure disposal of disused or spent radioactive sources and their proper management and regulation while they await disposal, is critical to mitigating the risk of intentional or accidental harm to people or the environment. Ideally the spent sources are repatriated by the producer of the sources, however this is often not the case and the country using the source has to take the necessary measures to secure it.[25] At BINA there is one disused gamma source dating back to1977. BINA has not been able to convince the source manufacturer to repatriate the source and has been successfully storing it since 1989 in a concrete cloth shielded room.

After the terror attacks in the US on 11 September 2001, concerns that radioactive material and sources would be used for malicious purposes resulted in strict international regulations being imposed on: (1) the shipment of gamma sources; (2) the production

23 Half-life is the time required for a radioactive substance to lose 50 percent of its radioactivity by decay.

24 For more information read the VCDNP Fact Sheet on the Sustainable Use of Radioactive Sources in Agriculture and Food Security. Available at: https://vcdnp.org/wp-content/uploads/2018/11/Fact-Sheet_27-Nov.pdf

25 For more information read the VCDNP Fact Sheet on the End of Life Management of Sealed Radioactive Sources. Available at: https://vcdnp.org/wp-content/uploads/2020/01/Fact-Sheet_DSRS_7-Jan.pdf

of gamma sources; and (3) the refurbishment of old gamma irradiators[26]. Fewer shipping companies are willing to take the risk of transporting radioactive cargo regardless of industry's compliance with national and international regulatory requirements and good transportation practices. Furthermore, because of significant consolidation within the shipping industry there are fewer routes available for the transportation of gamma sources.[27] Several medium-sized irradiation facilities in countries that do not produce radioactive sources have approached the IAEA for support in replenishing their cobalt-60 sources as the cost of the sources have become prohibitive and their availability limited.[28]

Alternative Technologies

International efforts to reduce the security risks related to gamma sources also include replacing isotopic radiation sources with non-isotopic alternatives. The most advanced and commercially viable alternative technologies for these applications are devices that use electricity to produce X-rays or electron beam (e-beam) radiation. Whilst the viability of alternative technologies for some applications has improved significantly, there are still limitations to the widespread implementation of most applications.[29] In developing countries the costs related to training, use and maintenance need to be reduced and the reliability and durability improved. The maintenance and recalibration of these machines require specialised skills, which are in short supply in most developing countries and could result in extended periods of down-time particularly for e-beam and ion-beam accelerators.[30]

In 2019 the IAEA published a report on recent achievements on irradiation facilities that provides examples of ways that accelerators can substitute radioisotope sources, specifically cobalt-60 and Cs-137. Examples include the complete substitution of cesium blood irradiators with X-ray systems in countries such as Norway and France, and in the USA where the conversion is successfully ongoing. Another example is medical linear accelerators (linacs), which have replaced cobalt-60 teletherapy for cancer treatment in many countries. In China more than one million tons of food per year is irradiated with e-beam. The report notes that high quality, reliable electricity sources are mandatory for these solutions.[31]

X-ray

Although the first mutagenesis experiments were made with X-rays, only 561 plant varieties created with X-rays are recorded on the MVD, whereas the database contains almost three times the amount created with gamma rays.

Cognisant of the challenges related to the transport and use of radioactive sources, the Plant Breeding and Genetics Laboratory (PBGL) of the Joint FAO/IAEA Division embarked on a series of investigations aimed at optimizing X-rays for plant mutagenesis. Their initial studies focused on adapting procedures to existing commercially available X-ray machines used in the medical field for this purpose. Ivan Ingelbrecht, the head of the PBGL is hopeful that their findings, contained in a handbook and recently submitted to the FAO for publishing, will find traction with the Member States of the IAEA and the FAO. He explained that affordable X-ray machine sources with sufficiently high dose rates enabling the irradiation of seeds in addition to in-vitro tissues, would facilitate wider dissemination of X-ray technology for plant mutation breeding to Member States. The reason being that seeds are the most widely used target for irradiation treatments.[32]

Heavy Ion Beam Irradiators

Heavy ion beam irradiation is commonly used in industrial applications, such as for the sterilization of medical equipment. In the 1990's Japan started using HIBI for plant mutation breeding.[33] Today China, Thailand, Bangladesh and Malaysia are also irradiating seeds and other plant materials with ion beams.

The Joint FAO/IAEA Division, in its manual on plant mutation breeding, cites a number of studies that have shown the many advantages of this technology including lower damage rate, higher mutation rate and wider and novel mutational spectrum.[34] Dr Azad explains that Binadhan-19 and Binadhan-14 are rare and novel mutations that resulted from irradiating the seeds with Japan's carbon ion beam accelerator. He also

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26 A new generation of X-ray irradiators for Insect Sterilisation. J. Econ. Entomol. 103(1): 85-94. Mastrangela T., Parker A.G., Jessup A., Pereira R., Orozco-Davila D., Islam A., Dammalage T. and Walder J.M.M. (2010).

27 International Irradiation Association contribution at a 2019 IAEA meeting on denials and delays of shipments of radioactive cargo.

28 Interview with Ms Valeriia Starovoitova: Radiation Technology Coordination Officer, Radioisotope Products and Radiation Technology Section, Division of Physical and Chemical Sciences, Department of Nuclear Sciences and Applications: IAEA

29 Non-Radioiosotopic Alternative Technologies White Paper, September 2019. U.S. Department of Homeland Security Cybersecurity and Infrastructure Security Agency. Available at: https://www.cisa.gov/sites/default/files/publications/19_1211_cisa_non_radioisotopic_alternative_technologies-white_paper.pdf

30 From interviews conducted with IAEA and country experts.

31 Recent Achievements on Irradiation Facilities Report of a consultant meeting IAEA Headquarters, Vienna, Austria 17 – 20 June 2019

32 Interview with Ivan Engelbrecht Head of the Plant Breeding and Genetics Laboratory of the FAO/IAEA Joint Division, IAEA.

33 Mutagenic effects of ion beam irradiation on rice. Hiroyasu Yamaguchi*1,3), Yoshihiro Hase2), Atsushi Tanaka2), Naoya Shikazono2,4), Konosuke Degi1,5), Akemi Shimizu1) and Toshikazu Morishita1,6), Breeding Science 59: 169–177 (2009). Available at: https://www.jstage.jst.go.jp/article/jsbbs/59/2/59_2_169/_pdf

34 Manual on Mutation Breeding, Third Edition Edited by Spencer-Lopes, M.M. Forster, B.P. and Jankuloski, L. Plant Breeding and Genetics Subprogramme Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture Vienna, Vienna, 2018

credits this accelerator with reducing the time required from ten years to four years for developing a new variety from seed to release. The science behind these findings are explained by Dr Azad in his paper on the use of HIBI for rice mutation breeding, in which he recommends further research to be conducted in this regard.[35] Dr Azad feels strongly about the benefits of HIBI as an alternative to gamma radiation based on his research and experience with this technology.

The IAEA TC Programme supported an expert mission in 2016 to Bangladesh to make recommendations on the potential of establishing an HIBI facility at BINA. The goal was to enhance BINA capabilities to create new cultivars, meeting the challenges of climate change and population growth. Dr. Liangdeng Yu, from the Thailand Center of Excellence in Physics, conducted the study. Whilst his findings were positive he noted that the HIBI recommended for BINA would cost 42 million USD, which does not include the cost of establishing the facility and training experts to use and maintain the equipment.[36] Bangladesh is on the United Nation's list of Least Developed Countries (LDCs)[37] and would require the support of its donor partners to purchase this technology.

LESSONS LEARNED FROM BANGLADESH

The following are lessons to be learned from Bangladesh's success in using nuclear technologies for plant mutation breeding:

1. To mitigate threats to food security and agriculture development and increase crop productivity, countries should invest in the development of national capabilities and expertise to research and apply innovative technologies that are safe, secure, and climate-smart.

2. Nuclear science and technologies used for plant mutation breeding have a long track record of increasing crop productivity and crop quality. These technologies enable the development of rare traits that increase the number of crop varieties that can be harvested in one season and make crops climate-smart, i.e. resistant to high temperatures, drought, winds, high-salinity in the soil, as well as require less irrigation.

3. The Joint FAO/IAEA Division develops and transfers technologies for plant mutation breeding and assists Member States to apply these technologies. The IAEA, for its part, also provides guidance and support for the safe and secure management, transportation and storage of the radioactive sources used for plant mutation breeding.

4. National nuclear institutions that develop and apply these technologies should be closely aligned with the national agricultural research and extension establishment to: influence agriculture policy; to have access to the broad selection of genetic material available in the country; and to ensure that the seeds developed are distributed through mainstream agriculture to farmers.

5. Close regional cooperation allows countries to exchange, within the limits of existing national policies, plant materials that are adapted and can grow in similar agroclimatic environments. This cooperation also allows the exchange of technology and sharing of expensive equipment.

INVESTING IN INNOVATION TO ENSURE THE CONTINUED USE AND ACCESS TO NUCLEAR TECHNOLOGIES FOR PLANT MUTATION BREEDING

The question that requires careful consideration is: what measures are required to ensure the continued access to nuclear technologies for plant mutation breeding? The challenges related to the transport of gamma sources may result in countries that do not produce these sources being unable to replenish them. Should this occur, the options for irradiation of seed and plant material for mutation induction include relying on regional partners, on the IAEA or using a viable alternative technology.

Reliance on regional partners could create a vulnerability in the agriculture sector to political changes in the region. In addition, as recently witnessed, transport delays and other complications caused by a global pandemic or a natural disaster are detrimental both to the economy on a broad scale and to the constituents on the ground, whose critical work is contingent on uninterrupted and ongoing research.

Reliance on the IAEA would require it to command more capacity and resources as countries increasingly turn to the IAEA for support and services they can no longer

35 Photoperiod-insensitive mutants with shorter plant height identified in the m1 generation of rice irradiated with carbon ion beams. Md. Abul Kalam Azad, SABRAO Journal of Breeding and Genetics 45 (2) 179-186, 2013. Available at: https://www.researchgate.net/publication/287350906_Photoperiodinsensitive_mutants_with_shorter_plant_height_identified_in_the_m1_generation_of_rice_irradiated_with_carbon_ion_beams

36 Report produced in 2016 by Dr. Yu, Liangdeng, IAEA Expert Senior Research Fellow, Thailand Center of Excellence in Physics.

37 According to a World Bank Report Bangladesh has made remarkable progress in reducing poverty, supported by sustained economic growth and is on track to graduate from LDC status by 2024.

obtain nationally or regionally. In Bangladesh, lack of access to gamma radiation, would impact negatively on BINA's research and development activities, which, as discussed in this paper, are a key component of Bangladesh's agriculture sector on which 170 million people depend.

Non-isotopic alternatives for plant mutation breeding have not benefited from the same demand and innovation as in the medical sector. More research is required to develop viable alternatives to gamma radiation used for plant mutation breeding.

Recommendations

- Availability of and access to X-ray technology with sufficiently high dose rates for seed irradiation can be an important step to further advance X-ray technology for mutation breeding by FAO and IAEA member states. An in-depth comparative study by the IAEA of the use of gamma and X-ray technology for plant mutation breeding is recommended. Such as study should provide the foundation for the further development of X-ray technology to ensure that this can be applied successfully as a routine technology in developing countries.

- Most of the data on the benefits of ion beam irradiation is being recorded in the Asia-Pacific region. More research is required in this regard and the cost of the technology should be weighed up against the benefits for crop improvement, which in the case of Bangladesh seems to be significant.

- Challenges related to the transportation of radioactive sources and the safe and secure management of disused sources should be addressed. IAEA Member States should are encouraged to make a commitment to the guidelines detailed in the Code of Conduct on the Safety and Security of Radioactive Sources as well as its Supplementary Guidance document on the management of disused radioactive sources. The IAEA with the International Maritime Organisation, convened a steering committee on the denials of shipment in 2006 which included industry and transport sector representatives. The Steering Committee addressed some of the pressing problems caused by transport restrictions at that stage but is no longer active. This Steering Committee should be revived in light of current developments.

IN CONCLUSION

The use of nuclear technology for plant mutation breeding is environmentally friendly and safe for human consumption and accessible to developing countries. Whilst chemical agents are also used for plant mutagenesis, and advances are being made on gene editing to develop new crop varieties, nuclear technologies such as gamma-ray or X-ray irradiation provide valuable complementary tools and comparative advantages as there are significant constraints to the use and/or the effectiveness of these processes, as mentioned earlier in this study. As the impact of climate change increasingly threatens crops and livelihoods globally, nuclear technology could become more important given the ability of radiation to produce mutations and create novel genetic diversity and to pave the way for the identification of genes contributing to specific traits.

The Joint FAO/IAEA Division has been the driving force behind plant mutagenesis for crop improvement and is essential to ensuring access to this technology for many developing countries. The research and development conducted, and the support provided by this division should continue to evolve to keep pace with innovations in science and technology and to meet the needs of the Member States.

One of the areas where the Member States can request more research and development by the IAEA is that of non-isotopic alternatives for plant mutation breeding. These technologies not only increase the security and thereby the long-term sustainability of nuclear applications for agriculture development, but they also provide an alternative to radioactive or isotopic sources that are becoming increasingly expensive and hard to come by.

The services delivered by the IAEA for crop improvement unequivocally demonstrates the benefits of being a member state of the IAEA. Nuclear science and technologies bring with them innovation that provides sustainable solutions to climate change, food security, hunger and countless other global problems that concern all of humanity. Every effort should be made to ensure the continued access to and use of these technologies by all countries.

Photo: Nicole Jawerth/IAEA