ATOMS FOR AGRICULTURE: ADVANCING FOOD SECURITY THROUGH NUCLEAR APPLICATIONS IN INDIA

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Agriculture plays a key role in ensuring food security, reducing poverty and supporting the economic development of a country. In India, the agricultural sector is particularly important, not only as a source of food, but also as a basis of livelihoods and economic growth. In 2016, agriculture accounted for 23 per cent of India's Gross Domestic Product (GDP) and employed 59 per cent of the country's total workforce.[1] But the challenges facing agriculture are many and multifaceted. With a rapidly growing population projected to exceed 1.5 billion by 2030 and 2 billion by 2050[2], India faces an urgent need to feed a growing population while managing limited resources and environmental concerns. To meet these challenges, innovative solutions that increase productivity, promote sustainability and conserve natural resources will be required.

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1. FAO (Food and Agriculture Organisation), "India at a Glance," Food and Agriculture Organisation of the United Nations, https://www.fao.org/india/fao-in-india/india-at-a-glance/en/. Accessed on November 25, 2024.
2. Shoba Suri, "The Implications of the Growing Population on Human Development in India," *ORF Expert Speak*, Observer Research Foundation, July 11, 2023, https://www.orfonline.org/expert-speak/the-implications-of-the-growing-population-on-human-development-in-india.

Through the use of isotopes and radiation techniques, nuclear applications help to increase crop yields, improve crop varieties, control pests and diseases, conserve land and water resources, and improve food safety and quality control.

While traditional farming methods are important, they face many constraints such as the decreasing availability of land, the effects of climate change and the escalating demand for resources. There are additional concerns: rising temperatures and sea levels, melting glaciers, changing river systems; and the spread of pest-related diseases are adding to the challenges for agricultural productivity. As the world's population grows towards an estimated 9.1 billion by 2050[3], the strain on agricultural systems will become increasingly evident, which will require different approaches to food and nutrition security. This is where nuclear technology comes in as a promising solution for modern agriculture.

Nuclear science and technology offer sustainable solutions to some of these problems in agriculture. Through the use of isotopes and radiation techniques, nuclear applications help to increase crop yields, improve crop varieties, control pests and diseases, conserve land and water resources, and improve food safety and quality control. This emerging field of "nuclear agriculture" has the potential to revolutionise traditional farming practices. "Nuclear agriculture" may sound like a science fiction premise from novels or comic books, but it is very real, based on science, and is already in practice.

This application has already been scientifically tested and proved beneficial in balancing environmental protection and sustainability. It also supports "climate-smart" agricultural practices, increasing the resilience of food systems to climate change by making them disease-resistant and increasing yields.

3. Ingrid Kirsten, *The Contribution of Innovative Nuclear Technology to Sustainable Agriculture Development* (Vienna Centre for Disarmament and Non-Proliferation, November 2020), https://vcdnp.org/wp-content/uploads/2020/11/Contribution-of-Innovative-Nuclear-Technology-to-Sustainable-Agriculture_final.pdf.

At the international level, the International Atomic Energy Agency (IAEA), in partnership with the Food and Agriculture Organisation (FAO), is promoting the safe and effective use of nuclear technologies in food and agriculture to support global food security and sustainable agricultural development. This collaboration between the IAEA and FAO demonstrates the efforts of two international organisations to promote the safe and appropriate use of these technologies at regional, national and international levels.[4]

BARC has developed numerous high-yielding, pest-resistant and climate-resilient crop varieties that have played an important role in increasing agricultural productivity and ensuring food security.

In India, the Bhabha Atomic Research Centre (BARC) has been instrumental in the advancement of nuclear agriculture, making significant contributions to crop improvement, plant studies, and food and crop management. For example, since the 1950s, BARC has developed efforts in mutation breeding, using ionising radiation such as X-rays, beta particles, gamma rays and electron beams to induce beneficial genetic variation in crops. Through these initiatives, BARC has developed numerous high-yielding, pest-resistant and climate-resilient crop varieties that have played an important role in increasing agricultural productivity and ensuring food security.[5]

While the existing literature on nuclear applications in agriculture has largely focussed on outlining their technical advantages and disadvantages, there remains a significant gap in addressing the broader set of factors that shape their adoption. Most of the current literature tends to attribute limited uptake to generalised notions of 'public fear', without adequately examining the more complex economic, institutional and logistical barriers that influence the wider commercialisation of these applications. While addressing public misconceptions is important, a more nuanced understanding is needed—

4. International Atomic Energy Agency (IAEA), "Food and Agriculture," https://www.iaea.org/topics/food-and-agriculture. Accessed on November 25, 2024.
5. Bhabha Atomic Research Centre (BARC), "Applications of Radiation in Nuclear Agriculture," https://barc.gov.in/pubaware/agri.html. Accessed on November 25, 2024.

one that considers how these technologies are shaped by broader systems of infrastructure and market readiness. This article aims not only to raise awareness of the benefits of nuclear technologies in agriculture and to address common misconceptions, but also to examine holistically the key constraints and enabling conditions for their wider adoption in India.

As stated by BARC, "The three pillars of agriculture are crop improvement, crop production and crop protection."[6] These pillars provide a comprehensive framework for addressing some of the challenges facing India's agricultural sector. Using nuclear applications, BARC is advancing each of these pillars to strengthen the agricultural landscape in India. In the area of crop improvement, plant mutation breeding is a key effort, using radiation-induced mutations to develop high-yielding, disease-resistant crop varieties adapted to diverse climates. To support crop production, techniques such as soil fertility optimisation using isotopes enable targeted fertiliser applications that maximise productivity while preserving the health of the environment. To protect and preserve crops, food irradiation plays a critical role in reducing post-harvest losses and ensuring the availability of produce, extending shelf life and addressing food security concerns. Additionally, techniques such as the Sterile Insect Technique (SIT) contribute to crop protection by offering an environmentally sustainable method of pest control that eliminates the need for excessive use of chemical pesticides. Taken together, these advances demonstrate how BARC is using nuclear technology to holistically improve agricultural outcomes and food security in India.

The following sections will explore each of these applications in more detail.

IMPROVING CROPS THROUGH PLANT MUTATION BREEDING

Consider the process of rolling a handful of dice and watching the random results unfold. Think of those dice as the genetic make-up of plants, with

6. Anuj Tripathi, Ashish Srivastava, Ashok Hadapad, Ramesh S. Hire, and Prasun K. Mukherjee, "Application of Radiation Technology for Improving Crop Productivity," in A.K. Tyagi and A.K. Mohanty, eds., *Non-Power Applications of Nuclear Technologies* [Bhabha Atomic Research Centre (BARC) October 2021], https://barc.gov.in/ebooks/9788195473328/paper04.pdf.

each roll representing the natural mutations that drive evolution and selective breeding. In 2007, Dr Pierre Lagoda, head of plant breeding and genetics at the IAEA, often used this simple analogy to explain plant mutation breeding. “That’s what nature does,” he stated, scattering four tiny dice on his desk to demonstrate how such genetic changes create diversity. But instead of waiting for nature to roll its dice over centuries, scientists like Dr Lagoda use radiation to speed up the process, creating improved crops that can resist disease, adapt to climate challenges and increase yields. This is achieved without introducing anything unnatural into the plants themselves. He explained, “I’m not doing anything different from what nature does. I’m not using anything that was not in the genetic material itself.”[7]

Dr Lagoda emphasised the simplicity and natural approach of the technique: “We are mimicking nature in this. We’re concentrating time and space for the breeder so he can do the job in his lifetime. We concentrate how often mutants appear—going through 10,000 to one million—to select just the right one.” Unlike more controversial approaches to genetic modification, such as GM crops, which involve the introduction of foreign DNA, radiation mutation breeding relies entirely on the plant’s existing genetic material. The process leaves no residual radiation and produces crops that are indistinguishable from those developed using conventional methods.[8] For decades, this technique has been quietly revolutionising agriculture.

This targeted approach to accelerating genetic variation represents a bridge between nature’s evolutionary processes and modern agricultural innovation. Plant mutation breeding “is a method that uses physical radiation or chemical means to induce spontaneous genetic variation in plants to develop new crop varieties.”[9] By exposing plant material and seeds

7. William J. Broad, “UN Scientists Using Radiation to Prod Nature into Producing Better Crops,” *New York Times*, August 29, 2007, https://www.nytimes.com/2007/08/28/health/28iht-sncrops.1.7286579.html.
8. Ibid.
9. Vladimir Tarakanov, “What Is Mutation Breeding?” IAEA, November 2, 2022, https://www.iaea.org/newscenter/news/what-is-mutation-breeding#:~:text=Plant%20mutation%20

to ionising radiation, such as gamma rays, X-rays or electron beams, this method induces changes in the plants' DNA, leading to the development of improved crop varieties. Unlike natural mutations, which occur slowly over long periods of time, radiation speeds up this process, allowing plant breeders to produce large populations of genetically diverse plants much more quickly.[10]

The key advantage of mutation breeding is its ability to rapidly generate a wide range of genetic variation. These variations are used to create new, improved crop varieties that better adapt to challenges such as climate change, and pest resistance, and yield improvement. Mutation breeding is a cost-effective, proven and environmentally friendly method that has stood the test of time.[11] It has been used for decades to successfully breed crops with desirable traits and remains a widely applicable technique in agricultural research today.

According to the IAEA, radiation induces changes in DNA that increase mutation rates 1,000 to 1 million-fold, enabling more effective plant breeding and more crop variation in less time.[12] It is this accelerated genetic variation that forms the basis of mutation breeding, one of the most effective ways of meeting the world's growing demand for food.

While advanced technologies such as gene editing offer targeted ways to alter specific genes, mutation breeding remains beneficial because it generates a broader genetic diversity that may not be achievable through gene editing alone. In other words, as Liqiu Ma, Fuquan Kong and others have argued, mutation breeding is a valuable tool because it introduces random genetic changes throughout the genome, increasing the chances of discovering useful traits that might otherwise be missed.[13] These changes can affect the plant at

breeding%2C%20also%20called,to%20develop%20new%20crop%20varieties. Accessed on November 25, 2024.

10. Ingrid Kirsten and Anthony Stott, *Ionising Radiation: Transforming Crops and Commerce in the 21st Century* (Vienna Centre for Disarmament and Non-Proliferation, n.d.), https://vcdnp.org/wp-content/uploads/2024/11/VCDNP-Sustainable-Solutions-Brief-1_web.pdf.
11. Tarakanov, n. 9.
12. Ibid.
13. Liqiu Ma, Fuquan Kong, Kai Sun, Ting Wang, and Tao Guo, "From Classical Radiation to Modern Radiation: Past, Present, and Future of Radiation Mutation Breeding," *Frontiers in Public Health 9*, 2021, p. 768071, https://doi.org/10.3389/fpubh.2021.768071.

the genetic, chromosomal or even DNA level, resulting in crops with more desirable traits such as improved yield, disease resistance, nutritional quality or faster ripening.

Although there are chemical methods of inducing mutations, the focus of this section is on nuclear techniques, such as radiation mutagenesis. Mutagenesis is simply defined as the formation of genetic mutations.[14] Chemical mutagenesis works by introducing chemical agents that interact with genetic material, often leading to point mutations at the gene level. While chemical mutagenesis has its uses, radiation mutagenesis "has the characteristics of more complex genetic mutations and more beneficial mutant phenotypes"[15]—simply put, it offers more complex and beneficial changes to the plant's genetic make-up, resulting in more valuable mutant traits. As well as developing thousands of crop varieties, mutation breeding has created vast genetic resources for all the world's major cereal and vegetable crops.

Plant Mutation Breeding in India

As Dr Lagoda explained, plant mutation breeding works by using radiation to accelerate the natural process of genetic mutation, similar to how nature creates genetic diversity through random changes. The key to making this process faster and more effective is the use of radioisotopes.

Radioisotopes are simply unstable forms of elements that release small bursts of energy in the form of radiation to transform into a more stable state (a radioisotope just means a radioactive isotope). This radiation has the ability to trigger genetic changes in plants. Most radioisotopes are produced artificially in research reactors, where target materials are exposed to intense particles such as neutrons or protons. This exposure causes the atoms in the material to become unstable and eventually emit radiation. This radiation can be in the form of alpha, beta or gamma rays.

14. Ashan Chathuranga Udage, "Introduction to Plant Mutation Breeding: Different Approaches and Mutagenic Agents," *Journal of Agricultural Sciences,* 16, no. 3, 2021, p. 466, https://doi.org/10.4038/jas.v16i03.9472.
15. Ma et al., n. 13.

Most radioisotopes are produced artificially in research reactors, where target materials are exposed to intense particles such as neutrons or protons.

As the atoms transform into a more stable form, they can be used in agriculture to induce mutations in plant DNA, speeding up the process of developing improved crop varieties.[16]

In the case of BARC's work, this process of using radioisotopes to induce mutations has been central to India's efforts to increase agricultural productivity. In India, BARC has been instrumental in using nuclear technologies to address agricultural challenges and improve food security. Since the 1950s, BARC has been involved in mutation breeding, which uses ionising radiation such as X-rays, beta particles, gamma rays and electron beams to induce beneficial genetic changes in crops.[17] This process accelerates mutations that would otherwise occur naturally over long periods of time, enabling scientists to develop high-yielding seed varieties tailored to specific agricultural needs. By releasing eight new crop varieties in collaboration with state universities in 2024, "in its 70th year, BARC has now dedicated a total of 70 crop varieties to the farmers and people of India."[18] Varieties of wheat and sesame *(til)* have now been developed and released for the first time by BARC.[19]

India's leadership in the production of radioisotopes has also played a critical role in supporting agricultural progress. Research reactors such as DHRUVA, CIRUS and APSARA at Trombay, along with power reactors operated by the Nuclear Power Corporation of India Ltd. and the

16. International Atomic Energy Agency (IAEA), "Radioisotopes," https://www.iaea.org/topics/nuclear-science/isotopes/radioisotopes#:~:text=Most%20radioisotopes%20are%20artificially%20produced,into%20the%20required%20chemical%20form. Accessed on November 25, 2024.
17. Anirudh Yadav, "The Role of Nuclear Technology in Agriculture Sector: Case Study of India," *International Journal of Research in Engineering and Applied Sciences*, 13, no. 7, 2023, https://euroasiapub.org/wp-content/uploads/IJREASAjuly2023-Ay.pdf.
18. "BARC Dedicates 8 New Trombay Crop Varieties to Farmers," Department of Atomic Energy India, December 11, 2024, https://dae.gov.in/barc-dedicates-8-new-trombay-crop-varieties-to-farmersbarc-dedicates-8-new-trombay-crop-varieties-to-farmers/. Accessed on April 20, 2025.
19. Ibid.

accelerator at the Variable Energy Cyclotron Centre in Kolkata, produce a wide range of radioisotopes. These isotopes are essential for various scientific applications, including agricultural research.[20]

The strategic focus on radiation-induced mutagenesis for genetic improvement has enabled BARC to address India's broader vision of food and nutrition security.

BARC's innovative work in mutation breeding has led to the development of new crop varieties through radiation-induced mutagenesis and recombination breeding. Between 1973 and 2022, BARC released 55 crop varieties, including groundnut, rice, mustard, cowpea, sunflower, jute, linseed, soybean, mungbean and pigeonpea (as mentioned earlier, now there is a total of 70 crop varieties). These varieties, known as Trombay varieties, have gained widespread public acceptance and are widely grown throughout the country. Their desirable traits include improved yield, increased nutritional content, larger seed size, seed dormancy, resistance to diseases and environmental stresses, and earlier maturity.[21] These improvements have been instrumental in increasing agricultural productivity and supporting the development of alternative cropping systems, thereby reclaiming previously uncultivated land and generating additional income for farmers.

The strategic focus on radiation-induced mutagenesis for genetic improvement has enabled BARC to address India's broader vision of food and nutrition security. In a BARC publication exploring radiation technology for the genetic enhancement of crop plants, Badigannavar et. al. claim that using this technique, hundreds of mutants with desirable agronomic traits have been developed in several crops, including oilseeds (groundnut, linseed, mustard, soybean, sunflower), pulses (cowpea, mungbean, pigeonpea, gram), rice and jute. Recombination breeding is when a genetic variant (mutant) is identified and crossed with another mutant or variety to incorporate the beneficial traits of both variants. Badigannavar et. al. state, "A judicious

20. Yadav, n. 17.
21. Ibid.

blend of mutation and recombination breeding has a greater potential in the genetic improvement of crop plants as exemplified by crop breeding efforts undertaken at BARC, Trombay".[22]

The improved traits in these crops include higher seed yield, improved nutritional content, larger seed size, disease resistance, tolerance to moisture stress, seed dormancy and early maturity. These improvements have not only increased crop productivity but have also enabled the development of alternative cropping systems, the reclamation of previously uncultivated land and an overall increase in farm income. By addressing key challenges in agriculture, BARC's work has contributed significantly to the broader goal of ensuring food and nutrition security in India.[23]

The spread of Trombay varieties has been made possible through collaborative efforts among BARC, the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities. This collaboration, formalised through synergistic research partnerships and Memoranda of Understanding (MoUs), has ensured effective development and widespread adoption of these varieties.[24] To further raise awareness, BARC participates in public engagement activities such as exhibitions, *kisan melas* and field demonstrations under its Public Awareness Programme on Peaceful Uses of Atomic Energy.

Mutation breeding has evolved significantly since its first experiments in the 1920s, driven by advances in science that have increased its efficiency and precision. As food security challenges intensify, it is important to continue to refine these techniques while implementing supportive policies and regulations to facilitate the adoption of modern breeding methods.

22. Anand M. Badigannavar, S. J. Jambhulkar, J. G. Manjaya, J. Souframanien, B. K. Das, Ashok M. Badigannavar, T. R. Ganapathi, and P. Suprasanna, "Radiation Technology for Genetic Enhancement of Crop Plants," in A. K. Tyagi and A. K. Mohanty, eds., *Non-Power Applications of Nuclear Technologies*, [Bhabha Atomic Research Centre (BARC), October 2021], https://barc.gov.in/ebooks/9788195473328/paper03.pdf.
23. Ibid.
24. Anand M. Badigannavar, T. R. Ganapathi, and T. K. Ghanty, "Nuclear Agriculture: Crop Mutant Varieties and Related Agri Technologies for Societal Benefits," in A. K. Tyagi and P. R. V. Rao, eds., *Atomic Energy in India: Achievements Since Independence* [Bhabha Atomic Research Centre (BARC) Publications, 2022], pp. 202–10.

As Ashan Udage states, "The effort exerted by the scientists on further development of mutation breeding with correct approaches will permit mankind to achieve the major goal of plant breeding, which will help global food security at large".[25]

CROP PROTECTION THROUGH FOOD IRRADIATION

There are many methods such as pasteurisation and pressure cooking that are well known for eliminating bacteria and pathogens in food. Similarly, ionising radiation is a powerful tool used to achieve the same result. This process, known as food irradiation, has become an essential technique for improving food safety and extending shelf life.[26]

Food irradiation is the process of exposing food to ionising radiation—such as gamma rays, X-rays or electron beams—under controlled conditions. Gamma rays and X-rays are types of short-wavelength radiation within the electromagnetic spectrum, which also includes radio waves, microwaves, infrared radiation, visible light and ultraviolet light. Gamma rays are produced by radioisotopes such as cobalt-60 and caesium-137, while electrons and X-rays are produced by electrically powered machines.[27] This process reduces harmful microbes, delays spoilage and extends the shelf life of various foods. Unlike traditional preservation methods, irradiation achieves these benefits without changing the temperature of the food (it is considered a "cold method" since it does not use heat to kill germs) or leaving chemical residues.[28] It also preserves the nutritional quality, taste and texture of food, making it a useful and effective method. More than 60 countries around the world now allow the use of food irradiation for a wide range of products, including spices, grains, fruits, vegetables and meat. Its

25. Udage, n. 14.
26. U.S. Environmental Protection Agency (EPA), "Food Irradiation," https://www.epa.gov/radtown/food-irradiation. Accessed on November 25, 2024.
27. Bhabha Atomic Research Centre (BARC), "Radiation Technology for Food & Agro Commodities: Frequently Asked Questions on Irradiated Food," https://barc.gov.in/pubaware/food.html. Accessed on November 25, 2024.
28. U.S. Centres for Disease Control and Prevention, "How Food Irradiation Works," February 27, 2024, https://www.cdc.gov/radiation-health/food-irradiation/index.html. Accessed on November 25, 2024.

applications are not limited to preservation but extend to improving food safety and facilitating international trade.[29]

The Radura symbol is an international logo that is used to represent packaged food that has been irradiated. The symbol shows a plant (dot and two leaves) in a closed package (circle) irradiated by ionising radiation which passes through the package to the food (dashed lines).

Fig 1

Source: U.S. National Library of Medicine, https://openi.nlm.nih.gov/detailedresult?img=PMC5302430_foods-05-00079-g001&req=4

BARC states that irradiated foods should be labelled with the following information:

Fig 2

PROCESSED BY RADIATION

NAME OF THE PRODUCT :
PURPOSE OF RADIATION PROCESSING :

OPERATING LICENCE NO. :

BATCH IDENTIFICATION NO. :
(BIN) (as provided by facility)

DATE OF PROCESSING :

Source: T. Saravanan, Atul Kumar Tyagi, and Ranjeet Singh, "Gamma Irradiation for Preservation of Food and Allied Products," in A. K. Tyagi and A. K. Mohanty, eds., *Non-Power Applications of Nuclear Technologies*, (BARC, 2021), https://barc.gov.in/ebooks/9788195473328/paper06.pdf.

29. World Nuclear Association, "Radioisotopes in Food & Agriculture," updated April 30, 2024, https://world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/radioisotopes-in-food-agriculture. Accessed on November 25, 2024,

Why Irradiate Food?

Understanding the need to irradiate food gets to the heart of how nuclear technologies quietly support everyday life. At first glance, the idea of irradiating food may sound alarming, but in reality, it's a scientifically proven way to make our food safer and extend its freshness. Food irradiation is a useful technique that addresses several food safety and preservation challenges. One of its main benefits is the prevention of foodborne illness. Irradiation effectively eliminates harmful bacteria and pathogens such as *Salmonella* and *Escherichia coli* (E. coli), which are leading causes of foodborne illness worldwide. By reducing microbial contamination, this process improves food safety and reduces the risk of food poisoning. In addition, food irradiation helps to extend the shelf life of perishable foods such as fruit and vegetables by destroying spoilage organisms. This shelf-life extension not only reduces food waste, but also ensures a more reliable and consistent food supply. In addition, irradiation serves as an alternative to chemical fumigants in controlling pests in or on food, particularly in tropical fruits and internationally traded commodities. By eliminating pests without leaving harmful residues, irradiation supports environmentally sustainable food preservation practices.

In addition to these benefits, food irradiation plays a crucial role in delaying germination and ripening, which further expands its applications in agriculture. In crops such as potatoes, irradiation prevents sprouting, reducing premature spoilage, while in fruit, it delays ripening, allowing longer storage and transport times. These applications are particularly important in reducing post-harvest losses and ensuring that food remains in optimum condition when transported over long distances. Irradiation also has sterilising properties that are valuable for specialised food storage, such as in medical contexts or emergency situations. Foods exposed to higher doses of radiation can be stored for longer periods without refrigeration, making them ideal for long-term storage and for hospital patients with compromised immune systems. It is interesting to note that sterilised food

Irradiation facilitates the export of food products while maintaining high standards of quality and safety. It is particularly effective in controlling pests of quarantine concern that could otherwise disrupt world trade.

is also used in space missions to provide astronauts with safe, long-lasting meals.[30]

Food packaging is also sterilised with radiation. In the Netherlands, for example, irradiation is used to kill bacteria in milk cartons.[31]

There is a lesser-known aspect and important advantage of irradiated foods: they are important in their use in international trade, and irradiation facilitates the export of food products while maintaining high standards of quality and safety. It is particularly effective in controlling pests of quarantine concern that could otherwise disrupt world trade. Many countries have adopted the use of irradiation because of its capacity to control pests.[32]

Table 1

Food irradiation applications		
Low dose (up to 1 kGy)	Inhibition of sprouting Insect and parasite disinfestation Delay ripening	Potatoes, onions, garlic, ginger, yam Cereals, fresh fruit, dried foods Fresh fruit, vegetables
Medium dose (1-10 kGy)	Extend shelf-life Halt spoilage, kill pathogens	Fish, strawberries, mushrooms Seafood, poultry, meat
High dose (10-50 kGy)	Industrial sterilisation Decontamination	Meat, poultry, seafood, prepared foods Spices, etc.

Source: World Nuclear Association, https://world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/radioisotopes-in-food-agriculture.

30. U.S. EPA, "Food Irradiation"; U.S. Food and Drug Administration, "Food Irradiation: What You Need to Know," updated May 3, 2024, https://www.fda.gov/food/buy-store-serve-safe-food/food-irradiation-what-you-need-know. Accessed on November 25, 2024.
31. n. 29.
32. International Atomic Energy Agency, "Food Irradiation," https://www.iaea.org/topics/food-irradiation. Accessed on November 25, 2024.

How Does Food Irradiation Work?

To understand the important role of food irradiation, it is important to understand how the process works. Food irradiation involves exposing food to one of three types of ionising radiation: gamma rays (from cobalt-60), electron beams or X-rays. In all these cases, the food passes through a radiation chamber on a conveyor belt, where it is exposed to the radiation beams but never comes into direct contact with the radioactive materials. The ionising radiation sends enough energy into the cells of any bacteria, mould or other pathogens in the food to break their chemical bonds, effectively killing or inactivating them. This process prevents the pathogens from multiplying and reduces the risk of foodborne illness and spoilage. The main components of an irradiation facility include the radiation source (cobalt-60 or an electron accelerator), a lifting system to move the food and a biological shield to prevent radiation from escaping the irradiation cell. The walls and ceiling of the cell are usually made of thick, high-density concrete to ensure that no radiation escapes into the environment and to protect the operators. In the case of gamma radiation, the source is often submerged when not in use, as water is an effective and inexpensive shielding material. Electron accelerators, on the other hand, can be turned on and off as needed, eliminating the need for shielding when not in use. The choice of irradiation method—gamma rays, electron beams or X-rays—depends on factors such as the type of food, the dose required and the throughput required, with each method having its own advantages in terms of penetration and efficiency for different foods.[33]

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33. Bhabha Atomic Research Centre, “Radiation Processing for Food Preservation,” https://www.mofpi.gov.in/sites/default/files/RadiationProcessingforFoodPreservation.pdf.pdf; n. 30.

Separating Fact From Fiction

Food irradiation offers significant health and convenience benefits, but there are widespread misconceptions about its impact on human health and the environment.[34] These misconceptions have been fuelled by years of public debate, media coverage and political discussion, making it difficult to distinguish scientific fact from fictional claims. Despite the substantial body of scientific evidence supporting its safety and efficacy, the technology continues to face scrutiny, with proponents and opponents often distorting the facts to suit their own agendas.[35] It is important to understand what this technology actually does and, more importantly, what it doesn't do, to move beyond myths and towards informed acceptance.

Proponents of food irradiation often present it as a solution to world hunger. However, opponents of the technology tend to exaggerate its potential risks. Many claim that eating irradiated food, or even living near an irradiation facility, could increase the risk of cancer. Others fear that food irradiation will be misused to make spoiled or unhealthy food appear fresh.[36] Unfortunately, these exaggerated claims have overshadowed the proven benefits of food irradiation.

The reality is that food irradiation has undergone extensive scientific evaluation and has been shown to be a safe and effective method of improving food safety. The process poses no risk to human health or the environment because the radiation used to treat food does not make it radioactive. Instead, it serves to eliminate harmful pathogens and extend the shelf life of food. A detailed BARC publication on food irradiation, which answers many of the common questions about the technique, states, "The irradiation process involves passing of food through a radiation field allowing the food to absorb desired adiation energy. The food itself never comes in contact with

34. Centre for Consumer Research, "Myths about Food Irradiation," June 28, 2017, https://ccr.ucdavis.edu/food-irradiation/myths-about-food-irradiation#:~:text=Irradiation%20by%20E%2DBeam%20and,that%20of%20other%20processing%20technologies.
35. Paisan Loaharanu, "Food Irradiation: Facts or Fiction?" IAEA Special Report, 1990, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull32-2/32205784448.pdf.
36. Ibid.

the radioactive material. Gamma rays, X-rays and electrons prescribed for radiation processing of food do not induce any radioactivity in foods".[37] The scientific evidence for the benefits of food irradiation is well documented and the technology has been endorsed by leading health organisations, including U.S. federal agencies and many intergovernmental organisations.[38]

In addressing common misconceptions, it may be helpful to distinguish between 'radioactive' and 'irradiated'. An analogy can help clarify the difference between irradiation and radioactivity. Think of an irradiated object as a book with a light shining on it, whereas a radioactive object is like a light bulb. A radioactive object generates radiation from nuclear processes taking place within it, just as a light bulb emits light from its own source. In contrast, irradiation is the process by which an object (such as food) is exposed to radiation from an external source, similar to how a book is illuminated by light. While the irradiation process can change certain properties of the object—such as killing germs in food—it does not make the object itself radioactive.[39]

Another common concern about food irradiation is the disposal of radioactive waste from the radiation sources used in the process. However, this is not a significant problem. The most common radiation sources used in food irradiation, such as cobalt-60 and caesium-137, decay over time into non-radioactive materials such as nickel and barium. Once the radioactivity has decreased to a safe level, the sources are returned to the supplier, who is responsible for their proper storage. There is, therefore, no ongoing problem of radioactive waste disposal associated with food irradiation facilities.[40]

The fear of a 'meltdown' in irradiation facilities, resulting in the release of harmful radiation into the environment is another myth surrounding food irradiation. The BARC publication states that this concern is unfounded, as it

37. n. 33.
38. n. 28.
39. "Radioactive vs Irradiated," Energy Education, n.d., https://energyeducation.ca/encyclopedia/Radioactive_vs_irradiated. Accessed on November 25, 2024.
40. n. 33.

is impossible for a gamma irradiator to experience a meltdown. Unlike nuclear reactors, the radioactive materials used in irradiators, such as cobalt-60, are non-fissionable and cannot cause an explosion. In addition, these materials are double encapsulated in stainless steel tubes to ensure that no radiation leakage can occur.[41]

The cost of setting up a commercial radiation processing facility is another factor that sometimes causes concern. While the initial investment for such a facility can range from Rs. 6 to 10 crore, this cost is justified by the long-term benefits of improved food safety and reduced food waste. Irradiation technology helps address critical challenges such as foodborne diseases, spoilage and food security, making it a valuable tool for sustainable agricultural practices.[42]

In summary, food irradiation is not a technique that "drenches food in a shower of radioactive gamma rays"[43] as sensationally claimed by some critics, but a gentle and non-invasive technique that is completely safe (in fact, the critic quoted in this sentence herself acknowledges that the process does not make the food radioactive). It is a science-based and safe technology that can significantly improve food safety and supply. While misconceptions and exaggerated claims about its risks persist, the technology has been shown to be effective in addressing food safety issues without posing a threat to human health or the environment. Public understanding of food irradiation needs to be based on evidence, not unfounded fears, to ensure that its benefits are fully realised. As summarised by Mr Loaharanu, former head of the Food Preservation Section in the Joint Food and Agriculture Organisation/International Atomic Energy Agency (FAO/IAEA) Division of Nuclear Techniques in Food and Agriculture, "The record shows that the technique [food irradiation] can help to address problems of food supply and safety—without being hazardous to the environment or human health".[44]

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41. Ibid.
42. Ibid.
43. Lee Rothberg, "New Jersey Opinion; The Case Against Irradiation of Food," *New York Times*, February 14, 1988, https://www.nytimes.com/1988/02/14/nyregion/new-jersey-opinion-the-case-against-irradiation-of-food.html.
44. Loaharanu, n. 35.

Food Irradiation in India

There are significant challenges in reducing post-harvest losses, with the Food Corporation of India estimating that 10-15 per cent of grain production is lost due to inadequate storage facilities. The Ministry of Food and Civil Supplies reports that around 22 per cent of wheat production is lost annually due to spoilage.[45] In this context, gamma irradiation technology has emerged as an important tool to improve food security and safety by reducing such losses in India.

The Department of Atomic Energy (DAE) and BARC have been at the forefront of research into radiation processing to extend the shelf life of various food products. BARC's studies have demonstrated the efficacy of radiation in preventing sprouting in crops such as potatoes and onions, which leads to significant loss of quality and nutritional value during storage. For fruits such as mango and pomegranate, phytosanitary treatments using radiation have enabled export and improved market access. For example, mango irradiation, which began in 2007, has been instrumental in meeting quarantine requirements for international trade. According to the Press Information Bureau of India, approximately 1,150 tonnes of mangoes were irradiated for export to the US in 2017. Furthermore, BARC has found irradiation-based crop improvement to be a complementary and efficient method alongside conventional plant breeding techniques.[46]

To support the uptake of radiation processing, the Board of Radiation and Isotope Technology (BRIT) is assisting entrepreneurs and industry to establish gamma irradiation facilities through MoUs. The BARC publication on radiation processing for food preservation states that the DAE has also developed two key technology demonstration units to showcase the practical applications of radiation processing.[47]

45. Yadav, n. 17.
46. Press Information Bureau, Department of Atomic Energy, "Radiation Technologies for the Prevention of Food Loss" Government of India, March 7, 2018. https://pib.gov.in/newsite/PrintRelease.aspx?relid=177097.
47. n. 33.

Recent studies have demonstrated the potential of irradiation to enhance the flavour and antioxidant properties of foods while extending the shelf life of minimally processed products, such as Ready-To-Cook (RTC) vegetables.

The Radiation Processing Plant at Vashi, Navi Mumbai, has a capacity of 30 tonnes per day and is primarily concerned with medium and high dose applications. It is used for microbial decontamination of spices, dry vegetable seasonings such as onion flakes and pet food. This facility, operated by BRIT since January 2000, is an example of India's capacity for large-scale food irradiation.

The Krushak (Krushi Utpadan Sanrakshan Kendra) facility in Lasalgaon, Maharashtra, was established to demonstrate low-dose radiation applications. These include sprout control in onions, insect disinfestation of cereals and pulses, and quarantine treatments for fresh fruits and vegetables. Krushak became the first cobalt-60 gamma irradiation facility outside the United States to be certified by the United States Department of Agriculture and Animal and Plant Health Inspection Service (USDA-APHIS) for the phytosanitary treatment of mangoes, allowing them to be exported to the United States after an 18-year hiatus.[48] As of September 2024, India has established 34 irradiation facilities that are operational in the country in private, semi-government and government capacity.[49]

In addition to these established facilities, research at BARC's Food Technology Division continues to explore innovative applications of radiation processing. Recent studies have demonstrated the potential of irradiation to enhance the flavour and antioxidant properties of foods while extending the shelf life of minimally processed products, such as Ready-To-Cook (RTC) vegetables. These products, which require minimal preparation by the consumer, are becoming increasingly popular due to their convenience.

48. Ibid.
49. Chirag Paswan, "How to Ensure Food Safety and Reduce Waste," *Indian Express*, September 4, 2024, https://indianexpress.com/article/opinion/columns/how-to-ensure-food-safety-and-reduce-waste-9548814/.

BARC has successfully demonstrated the use of radiation to improve the shelf life of several such minimally processed vegetables.[50] In the last decade, several facilities have come up in the private sector that also irradiate spices, cereals, pulses, and also allied products such as Ayurvedic herbs and herbal preparations.[51]

In the last decade, several facilities have come up in the private sector that also irradiate spices, cereals, pulses, and also allied products such as Ayurvedic herbs and herbal preparations.

It has already been established that food irradiation is a safe technique. To underline this claim, it is also worth noting that this technology has been approved by the Food Safety and Standards Authority of India (FSSAI), which manages the regulatory framework for food irradiation. It is actively "regulating the food safety aspects of irradiated food products under the Food Safety and Standards Act, 2016 and its Regulations thereunder."[52] These standards cover permissible sources, maximum allowable doses, packaging and labelling requirements. In fact, the FSSAI released a detailed guidance note in 2018 busting common myths surrounding food irradiation:

> Foods processed by radiation have been subjected to a thorough assessment of safety in national and international laboratories. These studies show that food irradiation presented no toxicological, nutritional or microbiological problems… In addition, a number of Scientific Bodies and Associations have also endorsed the safety of radiation processed foods. These include, the American Medical Association, American Gastroenterological

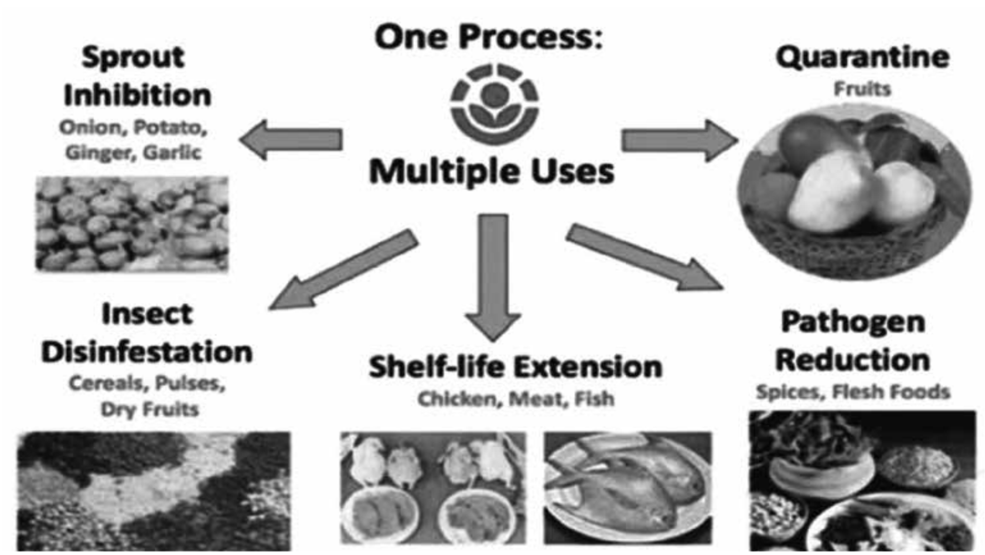
50. Sumit Gupta and Prasad S. Variyar, "Radiation in Food Processing," in Tyagi and Mohanty, eds., n. 6.
51. "Irradiated Food is Safe: Busting Myths Around It," Guidance Note No. 07/2018, Food Safety and Standards Authority of India, Government of India, https://fssai.gov.in/upload/uploadfiles/files/Guidance_Note_Irradiated_Food_Safe_24_12_2018.pdf. Accessed on April 20, 2025.
52. "Radiation Processing Technology," Press Information Bureau of India, Ministry of Food Processing Industries, July 19, 2017, https://pib.gov.in/newsite/PrintRelease.aspx?relid=168647. Accessed on April 20, 2025.

Association, American Dietetic Association, American Meat Institute, and Institute of Food Technologists.[53]

FSSAI approves this process to be undertaken for both domestic and export markets.

Due to the diverse applications of this technology, it is often referred to as "one process, multiple uses".

Fig 3



Source: "Irradiated Food is Safe: Busting Myths Around It," Guidance Note No. 07/2018, Food Safety and Standards Authority of India, Government of India, https://fssai.gov.in/upload/uploadfiles/files/Guidance_Note_Irradiated_Food_Safe_24_12_2018.pdf.

PROTECTING CROPS WITH THE STERILE INSECT TECHNIQUE

Insect pests are a major threat to agricultural productivity worldwide, causing significant pre- and post-harvest losses and spreading disease to

53. n. 51.

crops. Globally, crop losses due to insects are estimated to be around 10 per cent, and in the developing countries these losses can be much higher.[54] Despite the widespread use of chemical pesticides, insect-related food losses remain significant, often exceeding 40 per cent in some cases.[55] In addition, the overuse of pesticides has detrimental effects on ecosystems, including the development of pesticide resistance in insect species and the unintentional destruction of beneficial organisms that maintain ecological balance. This reliance on chemical methods also raises concerns about human health and environmental sustainability.[56]

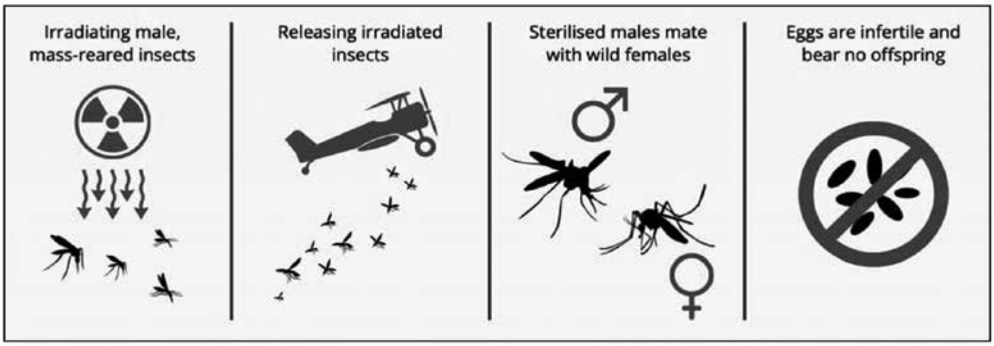
In this context, the Sterile Insect Technique (SIT) offers an innovative, environmentally friendly alternative to pest control. SIT involves the mass rearing of insects, followed by sterilisation using ionising radiation, and the systematic release of sterile males into pest-infested areas. When these sterile males mate with wild females, no offspring are produced, leading to a gradual reduction in the pest population. SIT is species-specific, targeting only the intended pests without harming other organisms, and is implemented on a large scale, covering both commercial crop production areas and surrounding habitats where pests may thrive.[57] Simply put, SIT means insect birth control.[58]

First proposed by American entomologist Dr. Edward Knipling in 1955, SIT was successfully used to eradicate the New World screwworm, a cattle pest, from North and Central America. Its success has since been extended to a wide range of applications, including the suppression or eradication of established pests and the prevention of invasive species. Countries such as Mexico, Chile, South Africa and the US have used SIT to significantly

54. n. 29.
55. International Atomic Energy Agency (IAEA), *Controlling Insect Pests with the Sterile Insect Technique*, IAEA Factsheet, Food and Agriculture (Vienna: International Atomic Energy Agency, August 2018), https://www.iaea.org/sites/default/files/19/02/controlling-insect-pests-with-the-sterile-insect-technique.pdf.
56. Yadav, n. 17.
57. n. 1.
58. P.V. Reddy and M. A. Rashmi, "Sterile Insect Technique (SIT) as a Component of Area-Wide Integrated Management of Fruit Flies: Status and Scope," *Pest Management in Horticultural Ecosystems*, 22, no. 1, 2016, pp. 1–11, https://krishi.icar.gov.in/jspui/bitstream/123456789/17467/1/SIT%20Review%20PMHE%20Reprint.pdf.

increase their agricultural exports, particularly of fresh fruits and vegetables.[59] This nuclear-derived technology supports sustainable pest management by reducing reliance on chemical pesticides, contributing to improved food security, environmental health, and agricultural trade.

Fig 4: SIT Application



Source: Ingrid Kirsten, and Anthony Stott. n.d. *Ionising Radiation: Transforming Crops and Commerce in the 21st Century* (Vienna Centre for Disarmament and Non-Proliferation), https://vcdnp.org/wp-content/uploads/2024/11/VCDNP-Sustainable-Solutions-Brief-1_web.pdf.

Klassen outlines several key requirements for the successful implementation of SIT. First, the target pest must be amenable to suppression by widespread integration of SIT with other pest control methods. Second, the pest should be amenable to mass rearing and its adult stage should not pose a threat as a pest or vector. In addition, a thorough understanding of the biology and ecology of the pest is important. Strong stakeholder cooperation and commitment to the campaign at the community level are also required, as well as the establishment of legal authority to ensure the implementation of the programme.[60]

59. Ibid.
60. W. Klassen, "Area-Wide Integrated Pest Management and the Sterile Insect Technique," in J. V. A. Dyck, A. S. Robinson, and A. Hendrichs, eds., *Sterile Insect Technique: Principles and Practice in Area-Wide Integrated Pest Management* (Vienna: IAEA, 2005), pp. 39–68, https://www.springer.com/gp/book/9781402033179.

The application of SIT for fruit flies can involve releasing both sterile males and females; however, research has shown that efficiency and cost-effectiveness improve significantly when only sterile males are released.[61] Large-scale field experiments with the Mediterranean fruit fly (*Ceratitis capitata*) demonstrated that sterile males are 3–5 times more effective in suppressing wild populations when released alone, compared to releases that included sterile females.[62]

The IAEA describes three key advantages of SIT over conventional chemical pest control, briefly explained below:

> Firstly, sterilised insects carry no potential to adversely affect the ecosystem, whereas pesticides can seriously harm both workers and the environment. Secondly, sterile insects neither establish themselves in the environment nor does the SIT kill beneficial non-target organisms; the techniques, therefore, integrate well with other biocontrol methods. Thirdly, the SIT can contain or eradicate invasive pest outbreaks sustainably, because it also reaches that last pest insect that pesticides cannot reach.[63]

SIT in India

As mentioned earlier in the chapter, agriculture is the cornerstone of India's economy, with a large proportion of the population dependent on farming and related activities. However, agricultural production faces many challenges, including damage caused by pests, diseases and weeds. In their BARC publication, Hadapad et. al. note that while the Green Revolution helped to increase crop yields and make India self-sufficient in food production, it also led to increased use of chemical pesticides. Given the limitations of Green Revolution technologies and

61. Kostas Bourtzis and Marc J. B. Vreysen, "Sterile Insect Technique (SIT) and Its Applications," *Insects*, 12, no. 7, 2021, p. 638, https://doi.org/10.3390/insects12070638.
62. Luke Alphey et. al., "Sterile-Insect Methods for Control of Mosquito-Borne Diseases: An Analysis," *Vector-Borne and Zoonotic Diseases*, 10, no. 3, 2010, pp. 295–311, https://doi.org/10.1089/vbz.2009.0014.
63. IAEA, "Controlling Insect Pests with the Sterile Insect Technique".

Given the limitations of Green Revolution technologies and the environmental concerns associated with pesticide use, there is a growing need for safer and more sustainable alternatives to support agricultural productivity.

the environmental concerns associated with pesticide use, there is a growing need for safer and more sustainable alternatives to support agricultural productivity.[64]

In response, India has actively pursued the development of SIT as a more environmentally friendly pest management strategy. BARC has been at the forefront of these efforts, working on SIT for the control of major pests such as the red palm weevil, potato tuber moth and fruit flies. For example, a recent SIT module for fruit fly control is being tested in Palghar district, Maharashtra, where researchers have profiled the distribution and population dynamics of fruit fly species and optimised mass rearing protocols and sterilisation doses.[65]

BARC has also made significant progress in developing SIT for other key pests. The red palm weevil, a major threat to coconut and other palm species, has been targeted with SIT and successful trials have been conducted in collaboration with agricultural universities in Maharashtra, Karnataka and Kerala. These trials have demonstrated a reduction in the weevil population and a decrease in the number of infested palms. Similarly, research into the use of SIT to control the potato tuber moth, a pest that attacks potatoes both in the field and in storage, has shown promising results, with significant suppression of the moth population following the release of sterile males. In fact, SIT was first used in India to control mosquitoes as early as 1973[66], and BARC continues to explore its application for other pests in collaboration with state agricultural universities.[67]

64 Ashok B. Hadapad, Arpit Prashar, Vrunda S. Thakare, and Ramesh S. Hire, "Sterile Insect Technique: An Eco-Friendly Insect Pest Control Strategy Based on Ionizing Radiation," in Santosh K. Sandur and Tapan K. Ghanty, eds., *Beneficial Effects of Ionizing Radiation in Biological Systems*, (Mumbai: Bhabha Atomic Research Centre, 2023), https://www.barc.gov.in/ebooks/9788196745363/paper20.pdf; Yadav, n. 17.

65. Ibid.

66. Reddy and Rashmi, n. 58.

67. Hadapad et al., n. 64.

Reddy and Rashmi note that while SIT was conceived and successfully demonstrated in the 1950s and has been effectively implemented in several countries, it has yet to gain significant traction in India. A key challenge is that mango exports remain restricted due to quarantine regulations related to the Oriental fruit fly (*Bactrocera dorsalis*). They highlight that SIT has considerable potential to address this by establishing fruit fly-free zones, which could significantly increase marketable yields and facilitate greater access to international markets.[68]

Improving and maintaining soil fertility is essential to ensuring food security and promoting environmental sustainability. One way to achieve this is through the use of nuclear and isotopic techniques

INCREASED CROP PRODUCTION THROUGH IMPROVED SOIL FERTILITY

Soil fertility is the inherent potential of a soil ecosystem to support optimal and sustainable plant growth, which directly influences crop yields. According to the IAEA, 95 per cent of the food we eat is grown either directly or indirectly from the soil, but this important and non-renewable source is threatened by many forms of soil degradation.[69] Improving and maintaining soil fertility is essential to ensuring food security and promoting environmental sustainability. One way to achieve this is through the use of nuclear and isotopic techniques, which provide valuable data on the movement and efficiency of fertilisers in soil, crops and water. By tracking the movement of labelled nitrogen and phosphorus fertilisers using isotopes such as nitrogen-15 and phosphorus-32, scientists can gain insights into fertiliser efficiency, nutrient uptake and environmental impact. These techniques help to determine the optimum amount of fertiliser needed to

68. Reddy and Rashmi, n. 58.
69. Artem Vlasov, "Nuclear Science Helps Enhance Soil Fertility for More Nutritious Food," *IAEA*, December 5, 2022, https://www.iaea.org/newscenter/news/nuclear-science-helps-enhance-soil-fertility-for-more-nutritious-food.

maximise crop yield while minimising the potential environmental damage caused by over-application, such as nutrient run-off or greenhouse gas emissions.

In addition to nitrogen and phosphorus, the carbon-13 isotope is used to track the incorporation of crop residues into the soil, helping to stabilise the soil and improve fertility.[70] By analysing isotopes of different elements, scientists can determine the precise fertiliser requirements of crops in specific environments. Excessive use of fertilisers not only reduces crop yields, but also leads to environmental problems such as pollution and the release of greenhouse gases.[71] Through studies using isotopic techniques, experts can develop guidelines for farmers on the appropriate fertiliser composition, dosage and frequency of application, ensuring the best use of resources. These efforts have made a significant contribution to increasing agricultural production and combating hunger and malnutrition, particularly in food-insecure regions.

The nitrogen-15 and phosphorus-32 isotopes are particularly effective in tracing the movement of nutrients between soil and plants. These isotopes provide quantitative data on the efficiency of fertiliser use by crops, helping to design better fertiliser application strategies. The nitrogen-15 technique also plays a crucial role in quantifying the nitrogen captured from the atmosphere by leguminous crops through biological nitrogen fixation, a natural process that further improves soil fertility.[72]

70. Ayushi Trivedi, Smita Agrawal, and Amit Kumar, "Soil Fertility: Improving Crop Yield through Nuclear Techniques," in Vikas Gupta, Rohit Pandey, Ankit Kumar, H. Chauhan, Astha Pandey, and Nazmeen Khanam, eds., *Soil Fertility and Its Management* (ISBN 9788119821051), https://www.researchgate.net/publication/379268097_Soil_fertility_improving_crop_yield_through_nuclear_techniques.
71. ForoNuclear, "Nuclear Techniques to Enhance Nutritional Content in Plants and Protect Soil Health," November 14, 2024, https://www.foronuclear.org/en/updates/in-depth/nuclear-techniques-to-enhance-nutritional-content-in-plants-and-protect-soil-health/#:~:text=Nuclear%20technology%20in%20agricultural%20production,countering%20the%20loss%20of%20fertility. Accessed on December 5, 2024.
72. International Atomic Energy Agency (IAEA), *Monitoring Soil–Water–Nutrient Interaction Using Isotope and Nuclear Techniques*, IAEA Factsheet, October 2018, https://www.iaea.org/sites/default/files/18/10/monitoring-soil-nutrient-interaction-using-isotope-and-nuclear-techniques.pdf.

In India, nuclear and isotopic techniques are being used to improve soil fertility and increase agricultural production. Scientists at institutions such as the Tamil Nadu Veterinary and Animal Sciences University have conducted studies using these techniques to analyse soil and water in different regions. Their research integrates soil science findings with livestock production and organic farming systems, helping farmers adopt more efficient and sustainable agricultural practices.[73] By working with scientists, Indian farmers are improving soil fertility and crop yields through these advanced nuclear methods. Mohammad Zaman, IAEA soil scientist and plant nutritionist, while talking about the project in Tamil Nadu, explains:

> Nuclear techniques are used to study agricultural processes in order to improve practices for farmers, and these studies are performed by trained scientists and experts under safe laboratory and glasshouse conditions… No radioactivity is passed on to the soil, or crop, as a result of this. Similarly, there is no residual radiation left in a plant after mutation induction through irradiation, so the final product is safe for consumption.[74]

FUTURE OUTLOOK

As India looks to make greater use of nuclear technologies in the agricultural sector, it is necessary to comprehensively assess their use. While the benefits of the various nuclear applications in the agricultural sector are clear, the path to commercial expansion requires a proper understanding of the opportunities and limitations.

For food irradiation, there may be significant potential for this technique to be applied on not only spices and export-oriented commodities such as mangoes. A new assessment is needed to determine which crops and foods should be explored for irradiation based on emerging demand patterns. With India's growing middle class, urbanisation and changing consumption

73. "Application of Nuclear Technologies in Agriculture Saw Positive Results in India: Mohammad Zaman," *Nuclear Asia*, December 13, 2017, https://www.nuclearasia.com/views/application-nuclear-technologies-agriculture-saw-positive-results-india-mohammad-zaman/1681/.
74. Ibid.

patterns, there is a growing market for fresh fruits, vegetables, meat and poultry products that require a longer shelf life without compromising safety or quality. In particular, fresh produce that is not easily preserved by conventional heat treatment—such as leafy greens, berries and soft fruits—could present a strong case for irradiation. The advantages of gamma radiation lie in its ability to preserve almost any packaged product without affecting its freshness or nutritional value. A less discussed, but very important aspect is the ability of irradiation to supply fresh and safe food to the Indian armed forces deployed in remote regions.

However, the limitations must also be clearly recognised. For example, it does not restore the freshness of spoiled or degraded products, nor should it be perceived as a replacement for basic hygiene and storage practices. Public confidence can easily be undermined if the technology is misused or inaccurately presented as a solution to poor food handling practices. In addition, products such as meat, poultry and certain fruits may still need to be refrigerated after irradiation to maintain safety and quality. In essence, food irradiation can complement traditional preservation methods, but not entirely replace them.

Additionally, infrastructure remains a bottleneck. In 2011, irradiated products were not widely available in the Indian domestic market. While the Union Budget for 2024-25 has taken an important initiative by allocating funds for 50 new multi-product food irradiation units in the Micro, Small and Medium Enterprises (MSME) sector[75], this expansion needs to be carefully managed. Developing irradiation facilities requires large initial capital investments, and new private players need to be assured through outreach and policy support that these investments can yield strong returns over time, and not to be deterred by the initial high costs. It makes a compelling business case to address the growing demand for safe food, together with the potential to reduce post-harvest losses, and increase export competitiveness.

Internationally, the motivations for introducing food irradiation vary considerably, highlighting how this is a ‘needs-based’ technology. While

75. Paswan, n. 49.

developed countries such as the United States prioritise it for food safety (elimination of pathogens such as *E. coli* and *Salmonella*), countries such as India and China see it more in terms of food security: minimising spoilage and extending marketability.[76] Since food irradiation is a needs-based technology, its use must be tailored to specific commodities, regions and gaps in the supply chain, and not treated as a one-size-fits-all solution. Moreover, each commodity must first be tested for its amenability to radiation processing in a laboratory since it cannot be applied to all kinds of food.

It is also important to note that the success of irradiation facilities depends on more than just the irradiation equipment itself. Adequate storage, transport and cold chain infrastructure must be integrated into the design and implementation. The benefits of irradiation will be severely limited without this holistic development of the technology.

Public perception remains one of the most critical barriers. In India, most consumers were noted to have "an open mind to radiation processed food. A small percentage of consumers were apprehensive about the technology. From the general comments made by the consumers, it appears that they were concerned about safety, cost, nutritional value and quality of radiation processed foods."[77] While there seems to be a general acceptance of irradiation of food in India, it is necessary to keep up the communication and outreach about its importance and benefits to maintain public confidence. The DAE is already engaged in several training programmes and other outreach efforts:

> The Department of Atomic Energy and its constituent units also undertake programmes to increase public awareness about the technology. The knowledge about the technology and the benefits of its radiation processing

76. Arun Sharma and P. Madhusoodanan, "Techno-commercial Aspects of Food Irradiation in India," *Radiation Physics and Chemistry*, 81, no. 8, August 2012, pp. 1208–1210, https://doi.org/10.1016/j.radphyschem.2011.11.033.
77. Board of Radiation & Isotope Technology, *Radiation Processing: Technical Information Document for Entrepreneurs* (Mumbai: Department of Atomic Energy, Government of India, 2014), https://www.mofpi.gov.in/sites/default/files/rpp-tecdoc.pdf.pdf.

India also needs to focus on strengthening its international collaborations. China currently supplies over 50 per cent of the world's irradiated food and has plans to construct an irradiation facility in Bangladesh.

of foods is spread through the awareness programmes using platforms offered by the various professional bodies, associations, and industry through seminars, symposia, and group discussions. These activities are also conducted in the regional languages. Special emphasis is laid on allaying the misconceptions and apprehensions about the technology in the minds of the public based on misguided fears.[78]

These are welcome initiatives, but it is a work in progress that must be sustained.

India also needs to focus on strengthening its international collaborations. China currently supplies over 50 per cent of the world's irradiated food[79] and has plans to construct an irradiation facility in Bangladesh.[80] In this context, India has a clear opportunity to carve out a larger space for itself. Being a leader in irradiation technology, it can consider exporting and offering support to other developing countries, especially those that emphasise peaceful nuclear applications. Since irradiation technology does not fall under the restrictions of the Nuclear Suppliers Group (NSG), India has greater freedom to expand these initiatives.

At the same time, it will be critical to continue maintaining the highest standards of nuclear safety and security. India must continue to adhere to IAEA safety standards and security guidelines, and actively support international conventions such as the Convention on Nuclear Safety and the Convention on the Physical Protection of Nuclear Material and its Amendment (CPPNM/A).

78. Ibid.
79. Ke Wang, Xinxin Pang, Zhengkui Zeng, Houhua Xiong, Jifu Du, Gang Li, and Isaac Kwasi Baidoo, "Research on Irradiated Food Status and Consumer Acceptance: A Chinese Perspective," *Food Science & Nutrition* 11, 2023, pp. 4964–4974, https://doi.org/10.1002/fsn3.3511.
80. World Nuclear News. "China to Supply Bangladesh with Irradiation Plant," June 17, 2024, https://www.world-nuclear-news.org/Articles/China-to-supply-Bangladesh-with-irradiation-plant. Accessed on April 27, 2025.

These guidelines must adequately and appropriately be communicated to the private sector as well. Maintaining a high level of safety credibility will be essential not only for domestic expansion, but also for international partnerships and market acceptance.

As India seeks to multiply its nuclear power output—from 8 GWe (Gigawatt electric) to 100 GWe by 2047—so too it needs to expand nuclear applications beyond energy, particularly in sectors such as agriculture that are central to national development and human well-being.

Unlike food irradiation, which is more readily available for commercial use, plant mutation breeding is a slower and more resource-intensive process. It requires breeders to work with large populations of plants, carefully screening them for rare and beneficial traits. The process is most effective when targeting traits that are visibly different and easy to detect (such as disease resistance) because these allow faster and simpler selection. In contrast, traits such as nutritional quality or taste, which require extensive testing, make the process much more difficult. The challenge is compounded by the low frequency of desirable mutations, which occur only about 0.1 per cent of the time.[81] These realities make mutation breeding a valuable but time-consuming approach that requires both scientific excellence and long-term institutional support.

As India seeks to multiply its nuclear power output—from 8 GWe (Gigawatt electric) to 100 GWe by 2047—so too it needs to expand nuclear applications beyond energy, particularly in sectors such as agriculture that are central to national development and human well-being. Nuclear technologies in agriculture, such as mutation breeding, food irradiation and soil fertility improvement, are no longer fringe innovations but proven tools that can strengthen food security. As such, the need of the hour is active support for their widespread use. However, for these applications to become

81. "Applications of Mutation Breeding," *e-Agriculture*, http://eagri.org/eagri50/GBPR211/lec28.pdf. Accessed on April 27, 2025.

more than pilot projects or anecdotal success stories, India must confront and address the techno-commercial bottlenecks, policy inertia and general public misconceptions that currently limit their large-scale adoption. A narrow focus on public perception is not enough; what is needed is a more integrated effort involving research organisations, regulators, private entrepreneurs and international partnerships. Such knowledge, both technical and regulatory, must no longer be restricted to just the scientific community, but be widely disseminated to the broader public. If India is serious about becoming a leader in both the food and nuclear future, then not only the government but all institutions at all levels must treat peaceful nuclear applications as core, not peripheral, to its development vision.