Use of radiation in food and agriculture

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Ensuring the food and nutritional security for the growing population of our country requires enhancement of food production and storage using advanced and affordable technologies. There is a need to develop new crop varieties having desirable traits such as higher yield, better disease/pest tolerance and resistance to abiotic stress. The development of improved and climate-resilient crop varieties using conventional breeding techniques depends on the inherent genetic variability of the crops. However, the genetic variability of a given plant can be enhanced by artificial induction of mutations using ionizing radiation. In India, Bhabha Atomic Research Centre, Mumbai has done substantial amount of work in mutation breeding aimed at the production of high-yielding and disease-resistant varieties of crops, especially oilseeds and pulses. Similarly, radiation technologies have been developed for the preservation and shelf-life extension of agricultural produce and food safety especially in controlling insect pests and microbes in food to prevent spoilage. Thus the nuclear technologies continue to make substantial contribution to food safety and security.

Keywords: Agriculture, crop improvement, food irradiation, mutant varieties, mutation breeding.

Introduction

FOR over 10,000 years, humans have been domesticating and selecting plants for cultivation to ensure food and nutritional security. The Green Revolution during the 1960s enabled the country to achieve higher agricultural yields, benefiting both farmers and consumers through intensive application of agricultural practices and crop improvement methods. Food production has since been significant, catering to the needs of the population. However, with the rapidly growing world population and diminishing land and water resources, coupled with climate change-driven environmental adversaries, there is an ever-increasing need to achieve higher agricultural productivity. Food security has thus become a high priority for developing nations. According to an estimate by the United Nations[1], the world's population is going to reach 10 billion by 2050, and this will require a significant rise in food production. There is a need for sustainable solutions to enable plant breeders to develop highly productive crops using conventional and modern methods of plant breeding, which include genetic and biotech interventions[2]. Breeding of crop plants relies upon the introduction of novel genetic variation for improving traits of relevance to crop improvement. India is an agrarian country with approximately 179.9 million hectares under cultivation[3]. In 2015, agriculture accounted for 14% of GDP and 11% of India's total exports[3]. Even though the total foodgrains production in the country reached an all-time high of over 260 million tonnes, India is confronted by the twin challenge of ensuring food security, while ensuring sustainable utilization of natural resources. Thus, there is a demand for integrated and innovative approaches to ensure sustainable food production.

Induced mutations for improving crop varieties

Plant breeding methods have contributed immensely to the development of genetically superior crop varieties and these continue to enrich the germplasm base of crop plants by evolving new and improved varieties for cultivation. Crop improvement is dependent upon selection, hybridization, recombination and mutation. Naturally occurring genetic variation often being low, there is a need to enhance variability using different techniques. Experimental mutagenesis was considered a breakthrough in the early 20th century, as an applied research frontier, paving the way for plant mutation breeding. Mutation induction using various physical (X-rays, gamma rays, alpha particles, fast neutrons, electron/ion beams and UV) and chemical (sodium azide, ethyl methane sulphonate, methyl methane sulphonate, hydroxylamine and *N*-methyl-*N*-nitrosourea) mutagens has become a tool in enhancing genetic variability in crop plants[4]. Mutation breeding has several advantages; it is cost-effective, quick, proven and robust. The induced changes are also transferrable and can be integrated with conventional breeding programmes. Moreover, the method is non-hazardous and environment-friendly, and has none of the perceived problems commonly ascribed to genetically modified (GM) crops.

Even though the manipulation of genetic material by wilfully inducing minor damage is practiced in mutation breeding, there is no transfer of genetic material from one species to another, which is employed in the generation of GM crops. GM crops are produced by intentional incorporation of a targeted change in plant traits, accomplished by the transfer of the gene sequence(s) from one species to another through genetic engineering techniques, including isolation, cloning and genetic transformation. Moreover,

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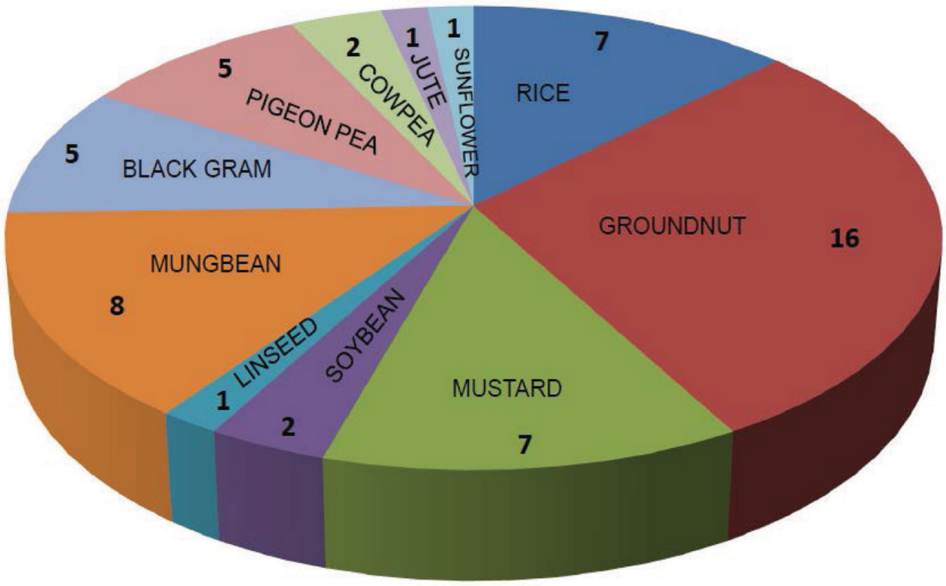

Figure 1. Mutant varieties developed by BARC, Mumbai and released for cultivation in India.

GM techniques are cost-intensive and attract environmental and biosafety concerns. On the other hand, the radiation-induced mutation technique only simulates what occurs in nature through spontaneous mutations; the only difference being the mere acceleration of the rate of mutation by an external means. In general, the changes are random and identification of a describable mutant is time-consuming using conventional phyenotypic features. However, the application of advanced molecular methods makes it possible to detect desirable mutants much more easily[5]. Even in cases where the desired mutants have not been obtained, a breeder can gainfully use the available mutants in carefully designed crossing experiments, which can give interesting results for the introgression of mutant traits[6].

Induced genetic variability in economically important plant species has resulted in the production and subsequent release of 3402 mutant varieties worldwide in about 180 plant species[7]. Induced mutations have been developed for various traits, including yield, early maturation, modification in plant architecture, root characteristics, oil and protein quality and seed size/colour. In comparison to cross-breeding methods, the induced mutation technique offers modification of a single or a few characters in an otherwise elite cultivar, without significantly changing the genetic make-up of the crop plants. Currently, induced mutation techniques are being combined with other methods such as the use of molecular markers and high-throughput mutation screening techniques, thereby becoming more powerful and effective in crop breeding programmes[2].

Several improved mutant varieties have been developed for cultivation in different crop plants, contributing to the economic gain in developing and developed countries[8,9]. Induced mutants are used either directly or indirectly in a breeding programme for the development of improved varieties for cultivation. In India, several mutant cultivars of crops, belonging to 56 plant species, have been released for cultivation. Among the mutants, majority is from ornamentals, followed by cereals, legumes and oilseeds. Mutation breeding efforts in cereals, legumes, oil crops, ornamentals and fruit trees have produced significant economic benefits[10–12].

At the Bhabha Atomic Research Centre (BARC), Mumbai, mutation breeding programmes for genetic improvement of crops began more than six decades ago, through the application of radiation technology[13]. About 55 improved crop varieties for various traits such as early maturity, large seed size, tolerance to biotic and abiotic stresses, high oil and protein content, and improved seed quality in oilseeds, pulses, cereals and other crops have been developed and released for commercial cultivation in different parts of the country by the Ministry of Agriculture, Government of India (Figure 1). These include rice (7), groundnut (16), mustard (7), soybean (2), sunflower (1), linseed (1), mung bean (8), black gram (5), pigeon pea (5), cowpea (2) and jute (1). The varieties released in these crops comprise direct mutants or mutant derivatives through inter-mutant or cultivar-mutant hybridizations.

BARC has contributed substantially to the development and release of a large number of mutant varieties that have been cultivated widely in different parts of India. The Trombay mutant crop varieties have high patronage among the farming community and are grown extensively in different parts of the country. At the national level, some of the Trombay varieties are popular as check varieties and are also employed as breeding lines in varietal development programmes. The most prominent contribution by BARC has been in groundnut through the development of early-maturing, confectionery-grade, large-seeded, export and consumption-oriented groundnut varieties such as TG 39, TPG-41, TLG-45 and RARS-T-1. For over a decade, more than 1600 tonnes of breeders' seeds of BARC varieties have been supplied to various seed agencies for multiplication and subsequent distribution to farmers. Using the mutant varieties of groundnut, farmers in Gujarat, Andhra Pradesh, Maharashtra, Karnataka, Odisha and Rajasthan have substantially increased their income, with 5000 kg/ha compared to 2000–3000 kg/ha obtained from local varieties, and net profits up to 1200 US$/ha (refs 13, 14). Another estimate indicates that 45% of Indian breeders' groundnut seeds are TG varieties (where T stands for Trombay, representing BARC), mostly TAG24, and the mutant groundnut varieties recorded seed production of 1022 metric tonnes worth US$ 1.18 million from 1998 to 2008 (refs 10, 11, 15).

Among pulse crops, the major accomplishment by BARC has been the development of the first Asian powdery mildew (PM) disease-resistant mungbean mutant variety (TARM-2), and yellow mosaic virus (YMV)-resistant mutants in black gram and mung bean through radiation mutagenesis[13,14]. The black gram variety 'TU-40' resistant to the yellow mosaic disease has been cultivated in more than 50% blackgram-growing area and has facilitated rice–fallow exploitation by marginal farmers, providing them with additional income. In pigeon pea, early maturing varieties 'TT-401' and 'TJT-501' have gained huge popularity among farmers in Madhya Pradesh, while the medium duration mutant variety 'PKV-TARA' has provided a reprieve to farmers in Maharashtra during prolonged monsoons. Together, these varieties have earned an average of 11% of the national breeder seed indent, with the highest peak (23%) in 2017–2018. In the case of cowpea, the Trombay mutant variety 'TRC-77-4' has desirable attributes of being a dwarf determinate plant type suitable for cultivation in Chhattisgarh, while another variety 'TC-901' has been notified for the North Zone under the National Network Project on Arid Legumes of ICAR, New Delhi[16].

In rice, mutant varieties 'TCDM-1', 'Vikram-TCR', 'CGJT' and 'TKR-Kolam' with desirable traits such as semi-dwarf nature and tolerance to lodging have been released for cultivation in Chhattisgarh and Maharashtra. In the oilseed crop mustard, a recently released mutant variety 'TBM204' has significant prospects of higher production benefit to mustard farmers in West Bengal. Several other Trombay mustard mutants are now being evaluated for stability and release. In linseed, a Trombay mutant variety 'TL-99' has a unique fatty acid composition with very low linolenic acid and has the potential to become an alternative source of edible oil[14].

In summary, radiation-induced mutation breeding has made outstanding contributions towards the development and deployment of high-yielding varieties, achieving significant societal impact.

Improved soil and plant health

Plant and soil health monitoring is an important aspect of agriculture to increase productivity and decrease environmental impact. Soil fertility is often maintained by fertilizers that supply the crop with essential plant nutrients to ensure optimal plant growth. Fertilizers labelled with nitrogen-15 (^{15}N) isotopes are employed to track and determine fertilizer uptake by plants[17,18]. Stable isotopes of carbon, hydrogen, nitrogen, oxygen and sulphur are also used to track production origins and contaminants in the agro-ecosystem and to monitor their origin and transport from soil to plants or water[19–21]. Further, Vander Zanden *et al.*[22] suggested that stable isotopic ratios (δ^2H and δ^{18}O) can be used for demarcating nutrient linkages and resource use across organisms and their ecosystems. Radioisotopes like carbon-13 (^{13}C) can be used under field conditions for studying the rate of organic decomposition and soil organic carbon (SOC) dynamics in ecosystems. Field-based monitoring of soil carbon levels can be accomplished using simple kits such as the soil carbon estimation kit developed by BARC, which is being used by farmers in several states of India[23].

The application of ionizing radiation for microbial strain improvement has great potential for enhanced biocontrol efficiency[24]. BARC has developed a mutant of the biocontrol agent *Trichoderma virens* (a plant-friendly fungus) using gamma irradiation. Extensive field data have shown that its use imparts significantly higher biotic and abiotic stress tolerance in a number of crop plants compared to its wild counterpart. This genetically improved biofungicide has three times better antifungal activity against plant diseases, and a formulation based on it called TrichoBARC has been successfully evaluated under field conditions in IGKV, Chhattisgarh, and BCKV, West Bengal[25]. The biopesticide – the first one to be developed by the induced mutation approach – has recently been accorded governmental approval for release to farmers.

Pest management

Irradiation, such as with gamma rays and X-rays, can be successfully used to sterilize mass-reared male insects so that while they remain sexually competitive, they cannot produce offspring after mating with normal females. It is important to note that the sterile insect technique (SIT) does not involve transgenic (genetic engineering) processes. Such nuclear-based technologies can be implemented on a large scale for agricultural insect pest management to support the intensification of crop production. BARC is developing SIT, which is an environment-friendly insect pest control method involving mass-rearing of male insects of a specific target pest and their radiation-induced sterilization. This is followed by the systematic area-wide release of the sterile male insects, where they will mate with wild females resulting in no offspring and a declining pest population[26]. The SIT protocols developed at BARC have been experimentally applied for the control of insect pests, including red palm weevil in coconut, potato tuber moth in potato and fruit flies. Currently, efforts are underway to develop methods to control other insect pests such as *Bactrocera dorsalis* and *Zeugodacus cucurbitae* and tomato leaf miner, *Tuta absoluta*[27].

Climate change adaptation

Climate change threatens to have an imminent impact on Indian agriculture with a rise in average air temperature and erratic monsoon rainfall. The impact is likely to involve frequent spells of drought, affecting soil health, crop growth, yield and food production[28]. Climate-smart agriculture needs to be adopted to ensure the management and improvement of crops for climate resilience, having better adaptability to thrive under harsh biotic and abiotic stresses[29]. Climate change also poses stresses of various kinds such as long periods of drought, seawater infiltration and new crop diseases/pests, which threaten crop varieties that are grown locally. It is to be emphasized that soil carbon sequestration under changed climatic conditions requires detailed studies, particularly with respect to different soil properties and related biophysical and microbiome functions[30,31].

Mutation breeding can potentially facilitate the development of new varieties of crops that are adapted to biotic and abiotic stresses, by inducing genetic changes that help plants perform better in harsh environments and to be resistant to evolving pathogens. Nuclear agricultural tools such as radiation-induced mutation breeding are being used to set the pace in breeding climate-smart varieties, while isotopic techniques are being used for agricultural water management. 'Climate-proof' mutant varieties in rice and common bean plants have been developed to tolerate high-temperature conditions and produce high yields[32]. Further, mutants having traits like early maturity, heat/drought tolerance, long-root system, etc. are desirable for growth under stress conditions[13].

Agriculture accounts for approximately 70% of freshwater use globally. Yet in many regions, the efficiency of water use is poor. With climate change and increasing demand for water from a growing population, there is a need for improving agricultural water use efficiency. The use of carbon-13, oxygen-18, hydrogen-2 (deuterium) and nitrogen-15 stable isotopes can be effectively employed for efficient agricultural water management, as they are used in developing water-saving (more crop yield per drop) strategies in different cropping systems and farming practices[33,34]. The importance of water availability in the rhizosphere has become critical, with climate change affecting rainfall patterns and crop production, particularly in water-scarce or water-stressed regions[35]. In this context, the use of cosmic-ray neutron sensors (CRNSs) for the assessment of landscape surface soil water has become increasingly important. Here, it is worthwhile to mention a radiation-polymerized hydrogel developed by BARC, which by its inherent gelling capacity, has been shown to enhance moisture retention in the root zone, aiding in effective water stress management. Its application in crop plants as well as in horticulture and floriculture practices is being evaluated for widespread adaptation. Radiation processing of biopolymers is an expanding area of R&D with extensive applications in agriculture and industry. BARC and Vasantdada Sugar Institute (VSI), Pune, have jointly developed irradiated chitosan for enhancing plant productivity in a wide variety of crops and successfully tested it under field conditions. Chitosan is a naturally abundant biopolymer and is easily available as a by-product of seafood processing. The irradiation process is environment-friendly and avoids the generation of waste residues, which are often seen with chemical processing methods. The irradiated chitosan has been successfully tested as a biostimulant for sugarcane, potato and onion as intercrops in sugarcane fields of Maharashtra[36]. The foliar application of irradiated chitosan has been shown to be effective for increasing yield and other traits in sugarcane under drought stress conditions[37], growth promotion and induction of stress tolerance in potato[38], and enhancing antioxidant properties combating resistance to purple blotch disease in onion[39].

Radiation technology for food preservation

Radiation technologies play an important role in food safety. Food preservation is an essential prerequisite for ensuring food security and safety. It is estimated that post-harvest loss of agricultural produce in India amounts to 10–30%, depending on the perishability of the produce[40]. For example, large amounts of grains are lost during storage[41]. After harvest, pulses are generally stored under dry conditions, where they are prone to infestation of insects, fungi, bacteria and rodents. According to FAO, Rome[42], insect damage in stored grains is about l0–50%. Fumigation is a commonly practised method of insect control in the case of stored cereals and pulses[43]. Chemical fumigants emit toxic gases which can kill all insects if done in a contained environment. Commonly used fumigants are methyl bromide, malathion, dichlorvos (which are being phased out in compliance with the Montreal Protocol), phosphine, carbonyl sulphide and sulphuryl fluoride. Though they are efficient, continued use of chemical fumigants can lead to the development of resistant pest strains. Moreover, some fumigants are not effective against bruchid insects (pulse weevils), which are common in stored pulses. Interestingly, bruchid infestation takes place when the crop is in the field itself, making their control difficult.

Table 1. Radiation processing plants in India

Plant	Purpose	Commissioning year
Radiation Processing Plant, BRIT, Vashi, Navi Mumbai, Maharashtra	Food and allied products	2000
KRUSHAK Irradiator, Lasalgaon, Nashik, Maharashtra	Food products	2002
M/S Organic Green Foods Ltd, Dankuni, Kolkata, West Bengal	Food, packaging and medical products	2004
M/S A.V. Processors Pvt Ltd, Ambernath (E), Thane, Maharashtra	Food and medical products	2005
M/S Universal Medicap Ltd, Vadodara, Gujarat	Food and medical products	2005
M/S Microtrol, Bengaluru, Karnataka	Food and medical products	2006
M/S Agrosurg Irradiators, Vasai, Thane, Maharashtra	Food, packaging and medical products	2008
M/S Gamma Agro Medical Processing, Hyderabad, Telangana	Food and medical products	2008
M/S Jhunsons Chemicals Pvt Ltd, Bhiwadi, Rajasthan	Agro, medical and packaging products	2010
M/S Innova Agri Bio Park Ltd, Malur, Kolar district, Karnataka	Food and medical products	2011
M/S Hindustan Agro Co-Operative Ltd, Rahuri, Ahmednagar, Maharashtra	Onion and other agricultural produces	2012
M/S Impartial Agro Tech (P) Ltd, Unnao, Lucknow, Uttar Pradesh	Food and medical products	2014
Gujarat Agro Industries Corporation Ltd, Bavla, Ahmedabad, Gujarat	Food products	2014
M/S Aligned Industries, Dharuhera, Rewari, Haryana	Food products	2015
Maharashtra State Agricultural Marketing Board, Navi Mumbai, Maharashtra	Food products	2015
M/S Pinnacle Therapeutics Pvt Ltd, Ahmedabad, Gujarat	Food and medical products	2018
M/S Electromagnetic Industries, Vadodara, Gujarat	Food products	2019
M/S Avantee Mega Food Park, Devas, Madhya Pradesh	Food products	2019
M/S Shriram Applied Radiation Centre, Delhi	Food and medical products	1990 (medical) 2016 (food)
M/S Jamnadas Industries, Indore, Madhya Pradesh	Food and allied products	2020
M/S Microtrol Sterilisation Services Pvt Ltd, Bawal, Haryana	Food and allied products	2021
M/S Andhra Pradesh Med Tech Zone Ltd, Vishakhapatnam, Andhra Pradesh	Food and allied products	2021
M/S Solas Industries, Kosi Kalan, Mathura, Uttar Pradesh	Food and allied products	2021
M/S AV Gamma Tech LLP, Ambernath, Maharashtra	Food and allied products	2021

Radiation processing of food entails exposing it to a pre-determined dose of ionizing energy, which passes through the food leaving no residual radioactivity[44]. Ionizing radiation such as electron beams, X-rays, and gamma rays can be effectively used for food preservation. Since acceptance by the United Nations Codex Alimentarius Commission in 1983 that foods irradiated below a certain level (10 kGy) are safe and nutritious, food irradiation is treated legislatively as a process and not as an additive. Radiation processing by ionizing radiation provides an effective method to control food losses[45,46]. Radiation processing of food is a non-thermal method, which causes minimal changes in sensory qualities, thereby maintaining food palatability and nutritional adequacy. It offers an effective alternative to chemical-based fumigation that has serious consequences on the environment and human health. The radiation-based method is implemented by exposing food or food products to a controlled dose of ionizing radiation for achieving the following objectives: (1) insect disinfestation of dried stored products or grains, (2) phytosanitation to overcome quarantine barriers in fruits and vegetables, (3) delay in ripening and senescence of fruits, (4) inhibition of sprouting in tubers, bulbs and other rhizomes, (5) increasing the shelf-life by elimination of spoilage-causing microbes, and (6) destruction of pathogens and parasites. Radiation processing can also have applications for the hygienization and sterilization of non-food items, including cut-flowers, pet food, cattle feed, fish feed, ayurvedic herbs, medicines and packaging materials. The method can be used for sterilization of foods meant for long-term storage in the absence of refrigeration. Interestingly, radiation processing is commonly employed in food meant for consumption by specialized categories of people, such as immunocompromised patients and astronauts. Meat consumed during space flights is preserved by a process called radappertization, wherein a calibrated dose of ionizing radiation is applied, sufficient to reduce the microbial activity to undetectable levels.

BARC has set up a major facility (KRUSHAK, Krushi Utpadan Sanrakshan Kendra), primarily for irradiation of fresh agricultural produce (such as onion and potato) at Lasalgaon, Nashik district, Maharashtra. Since 2007, KRUSHAK has facilitated the irradiation of mangoes for export to USA. In addition, feasibility studies have been conducted to extend the technology to other commodities such as litchi and pomegranate. Another radiation processing facility at Vashi, Navi Mumbai, has been in operation since 2000 for processing spices and dry ingredients for microbial decontamination. In India, about 24 irradiation plants have either been set up or are in different stages of construction in the private sector (Table 1).

There is widespread apprehension about the safety of irradiated food for human and animal consumption. It is important to note that the safety of irradiated food has been established by a number of experimental campaigns conducted by organizations such as the US Food and Drug Administration (USFDA)[47]. USFDA had evaluated and confirmed the safety of radiation processing of food using long-term experiments. Similarly, the World Health Organization, Centre for Disease Control and Prevention, and US Department of Agriculture have endorsed the safety of irradiated food[48]. Studies carried out by a number of Indian and international scientists have generated data that confirm the safety of radiation-processed food[49,50].

Summary

Among the various non-power applications of nuclear energy, use of radiations in food and agriculture has been quite substantial. Nuclear energy can be effectively used not only for enhanced production of food through seed improvement, but also for protecting crops against pests and disease-causing organisms. In the post-harvest scenario, nuclear energy can be used to minimize food spoilage caused by natural processes or by storage pests. Irradiation can be used to derive benefits not achievable by other conventional techniques[44]. As it is still an underexploited technology, there should be concerted action by the industry, government and consumer agencies to take the benefits to the people for ensuring food security and food safety for our growing population.

1. FAO, *The Future of Food and Agriculture – Trends and Challenges*, Food and Agriculture Organization of the United Nations, Rome, Italy, 2017; ISBN 978-2017. 92-5-109551-5.
2. Suprasanna, P., Saddhe, A., Ghuge, S. A. and Ingle, K. P., New and novel genetic tools for improving crops. *CAB Rev.*, 2021, **16**, 028; doi:10.1079/PAVSNNR202116028.
3. Chaturvedi, B. K. and Anil Raj, T. A., Agricultural storage infrastructure in India: an overview. *IOSR J. Bus. Manage*., 2015, **17**(5), 37–43.
4. Mba, C., Afza, R., Bado, S. and Mohan Jain, S., Induced mutagenesis in plants using physical and chemical agents. In *Plant Cell Culture* (eds Davey, M. R. and Anthony, P.), John Wiley, Oxford, UK, 2010, pp. 111–130.
5. Irshad, A., Guo, H., Zhang, S. and Liu, L., TILLING in cereal crops for allele expansion and mutation detection by using modern sequencing technologies. *Agron. J.*, 2020, **10**, 405; doi:10.3390/agronomy10030405.
6. Ma, L., Kong, F., Sun, K., Wang, T. and Guo, T., From classical radiation to modern radiation: past, present, and future of radiation mutation breeding. *Front. Public Health*, 2021, **9**, 768071; doi:10.3389/fpubh.2021.768071.
7. https://nucleus.iaea.org/sites/mvd/SitePages/Search.aspx (accessed on 27 April 2022).
8. Kharkwal, M. C. and Shu, Q. Y., The role of induced mutations in world food security. In *Induced Plant Mutations in the Genomics Era*, FAO, Rome, Italy, 2009, pp. 33–38.
9. Jain, S. M. and Suprasanna, P., Induced mutations for enhancing nutrition and food production. *Gene Conserv*., 2010, **40**, 201–215.
10. Ahloowalia, B. S., Maluszynski, M. and Nichterlein, K., Global impact of mutation-derived varieties. *Euphytica*, 2004, **135**, 187–204.
11. D'Souza, S. F., Reddy, K. S., Badigannavar, A. M., Manjaya, J. G. and Jambhulkar, S. J., Mutation breeding in oilseeds and grain legumes in India: accomplishments and socio-economic impact. In *Induced Plant Mutations in the Genomics Era* (ed. Shu, Q. Y.), IAEA, Vienna, Austria, 2009.
12. Bradshaw, J. E., Mutation breeding. In *Plant Breeding: Past, Present and Future*, Springer, Cham, 2016, pp. 529–560.
13. Souframanien, J. S. and Ganapathi, T. R., Mutation breeding in India: accomplishments and socio-economic impact. *Plant Breed. Genet. Newsl.*, 2021, **46**, 23–25.
14. Badigannawar, A. M. *et al.*, Radiation technology for genetic enhancement of crop plants. In *Non-Power Applications of Nuclear Technologies* (eds Tyagi, A. K. and Mohanty, A. K.), BARC, Mumbai, 2021, pp. 33–49.
15. Sarsu, F., Bimpong, I. K. and Jankuloski, L., Contribution of induced mutation. *Adv. Cienc. Ingen.*, 2021, **12**(3), 10; https://doi.org/10.18272/aci.v12i3.2031.
16. Dhanasekar, P. and Reddy, K. S., Development of Trombay cowpea variety 'TC-901' amenable for summer cultivation by induced mutagenesis. In FAO/IAEA International Symposium on Plant Mutation Breeding and Biotechnology, IAEA, Vienna, Austria, 27–31 August 2018, IAEA-CN-263-170.
17. Gardner, J. B. and Drinkwater, L. E., The fate of nitrogen in grain cropping systems: a meta-analysis of 15N field experiments. *Ecol. Appl*., 2019, **19**(8), 2167–2184.
18. Marlee, A., Trandel, A. V., Walters, S. A., Lefticariu, M. and Kinsel, M., Nitrogen isotope composition, nitrogen amount, and fruit yield of tomato plants affected by the soil–fertilizer types. *ACS Omega*, 2018, **3**(6), 6419–6426.
19. Shrivastava, M., Ramachandran, V. and D'Souza, S. F., Role of isotopes in soil-plant, water and fertility research. *IANCAS Bull.*, 2007, **VI**, 341–346.
20. Xenia, G. *et al.*, Assessment of multiple stable isotopes for tracking regional and organic authenticity of plant products in Hesse, Germany. *Isot. Environ. Health Stud.*, 2021, **57**(3), 281–300.
21. Sankoh, A. A., Derkyi, N. S. A., Frazer-Williams, R. A. D., Laar, C. and Kamara, I., A review on the application of isotopic techniques to trace groundwater pollution sources within developing countries. *Water*, 2022, **14**, 35; https://doi.org/10.3390/w14010-035.
22. Vander Zanden, H. B., Soto, D. X., Bowen, G. J. and Hobson, K. A., Expanding the isotopic toolbox: applications of hydrogen and oxygen stable isotope ratios to food web studies. *Front. Ecol. Evol*., 2016, **4**, 20; doi:10.3389/fevo.2016.00020.
23. Mehetre, S. T. and Chattopadhyay, S., Role of BARC technologies in agriculture for benefit of farming community in India. In Techno-Societal 2016 – Proceedings of the International Conference on Advanced Technologies for Societal Applications (ed. Pawar, P. M.), Springer International Publishing, AG, 2018, pp. 11–15.
24. Mukherjee, P. K., Induced mutation for genetic enhancement of the plant beneficial fungi *Trichoderma* species. *IANCAS Bull*., 2020, **XV**(1), 35–38.
25. Mukherjee, P. K. *et al.*, A novel seed-dressing formulation based on an improved mutant strain of *Trichoderma virens*, and its field evaluation. *Front. Microbiol*., 2019, **10**, 1910; doi:10.3389/fmicb.2019.01910.
26. Dyck, V. A., Hendrichs, J. and Robinson, A. S. (eds), *Sterile Insect Technique: Principles and Practice in Area-Wide Integrated Pest Management*, CRC Press, Boca Raton, USA, 2021, 2nd edn; https://doi.org/10.1201/9781003035572.
27. Hadapad, A. B. and Hire, R. S., Development of eco-friendly sterile insect technique for agriculturally important insect pests. *IANCAS Bull*., 2020, **XV**(1), 55–59.
28. Raza, A., Razzaq, A, Mehmood, S. S., Zou, X., Zhang, X., Lv, Y. and Xu, J. Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. *Plants*, 2019, **8**(2), 34; doi:10.3390/plants8020034.
29. Lipper, L. and Zilberman, D., A short history of the evolution of the climate smart agriculture approach and its links to climate change and sustainable agriculture debates. In *Climate Smart Agriculture. Natural Resource Management and Policy* (eds Lipper, L. *et al.*), Springer, Cham, Switzerland, 2018, vol. 52, pp. 13–30.

30. Filser, J. *et al*., Soil fauna: key to new carbon models. *Soil*, 2016, **2**, 565–582.
31. Baveye, P. C., Schnee, L. S., Boivin, P., Laba, M. and Radulovich, R., Soil organic matter research and climate change: merely restoring carbon versus restoring soil functions. *Front. Environ. Sci*., 2020, **8**, 579904; doi:10.3389/fenvs.2020.579904.
32. https://www.iaea.org/newscenter/news/scientists-develop-new-climate-proof-crops-with-help-of-nuclear-technology (accessed on 27 April 2022).
33. Sun, Z. J., Livingston, N. J., Guy, R. D. and Ethier, G. J., Stable carbon isotopes as indicators of increased water use efficiency and productivity in white spruce (*Picea glauca* (Moench) Voss) seedlings. *Plant Cell Environ*., 1996, **19**(7), 887–894.
34. Li, C., Huang, M., Liu, J., Ji, S., Zhao, R. and Zhao, D., Isotope-based water-use efficiency of major greening plants in a sponge city in northern China. *PLoS ONE*, 2019, **14**(7), e0220083; https://doi.org/10.1371/journal.pone.0220083.
35. Zeppenfeld, T., Balkenhol, N., Kóvacs, K. and Carminati, A., Rhizosphere hydrophobicity: a positive trait in the competition for water. *PLoS ONE*, 2017, **12**(7), e0182188; https://doi.org/10.1371/journal.pone.0182188.
36. Dalvi, S. G. and Suprasanna, P., Studies on radiation processed polymers mediated biochemical and molecular responses and relevance to enhancing plant productivity. In *Radiation-Processed Polysaccharides: Emerging Roles in Agriculture* (ed. Naeem, G.), Academic Press, Elsevier, UK, 2021, pp. 335–369.
37. Mirajkar, S. J., Dalvi, S. G., Ramteke, S. D. and Suprasanna, P., Foliar application of gamma radiation processed chitosan triggered distinctive biological responses in sugarcane under water deficit stress conditions. *Int. J. Biol. Macromol.*, 2019, **139**, 1212–1223.
38. Muley, A. B., Shingote, P. R., Patil, A. P., Dalvi, S. G. and Suprasanna, P., Gamma radiation degradation of chitosan for application in growth promotion and induction of stress tolerance in potato (*Solanum tuberosum* L.). *Carbohydr. Polym.*, 2019, **210**, 289–300.
39. Gaikwad, H. D., Dalvi, S. G., Hasabnis, S. and Suprasanna, P., Electron beam irradiated chitosan elicits enhanced antioxidant properties combating resistance to purple blotch disease (*Alternaria porri*) in onion (*Allium cepa*). *Int. J. Radiat. Biol.*, 2022, **98**(1), 100–108.
40. Kumar, D. and Kalita, P., Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. *Foods*, 2017, **6**(1), 8; https://doi.org/10.3390/foods6010008.
41. Singh, G. and Sharma, R. K., Alternatives to phosphine fumigation of stored grains: the Indian perspective. *Himachal J. Agric. Res*., 2015, **41**(2), 104–113.
42. FAO, Global initiative on food losses and waste reduction, Food and Agriculture Organization of United Nations Rome, Italy, 2014.
43. Mohapatra, D., Kar, A. and Giri, S. K., Insect pest management in stored pulses: an overview. *Food Bioprocess Technol.*, 2015, **8**(2), 239–265.
44. Ehlermann, D. A. E., The early history of food irradiation. *Radiat. Phys. Chem*., 2016, **129**, 10–12.
45. Gautam, S. and Tripathi, J., Food processing by irradiation – an effective technology for food safety and security. *Indian J. Exp. Biol*., 2016, **54**, 700–707.
46. Tripathi, J. and Variyar, P. S., Effect of gamma irradiation on the shelf-life and physico-chemical quality of ready-to-cook (RTC) drumstick (*Moringa oleifera*) pods. *LWT – Food Sci. Technol.*, 2018, **88**, 174–180.
47. https://www.fda.gov/food/irradiation-food-packaging/overview-irradiation-food-and-packaging (accessed on 26 April 2022).
48. Ravindran, R. and Jaiswal, A. K., Wholesomeness and safety aspects of irradiated foods. *Food Chem*., 2019, **285**(2019), 363–368.
49. Diehl, J. F., *Safety of Irradiated Foods*, Marcel Dekker, New York, USA, 1995.
50. Grégoire, O. *et al.*, Radiological safety of food irradiation with high energy X-rays: theoretical expectations and experimental evidence. *Radiat. Phys. Chem*., 2003, **67**, 169–183.

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