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Nuclear Technology in Plant Breeding: Evaluating Radiation Effects on Genetic Diversity and Stability

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ABSTRACT: Plant breeding is a fundamental strategy for food security, adaptation to climate change, and sustainable crop production. The limitations of conventional breeding methods, particularly the restriction of genetic diversity and the long-time requirement, have necessitated the application of novel technologies. The application of nuclear technology, specifically the induction of mutations through radiation, is considered an effective tool for increasing genetic diversity and selecting desirable traits. This review article analyzes the evaluation of radiation effects on genetic diversity and stability in plant breeding. In this article, the mechanism of radiation action, the process of determining the appropriate dose, the types of induced mutations, and the relationship between genetic diversity and stability are explained in detail. Additionally, international experiences of nuclear technology application, the importance of this technology for Afghanistan, and recommendations for future research are presented. The results indicate that the application of an appropriate radiation dose can contribute to increasing genetic diversity; however, maintaining genetic stability and controlling undesirable mutations are fundamental factors for the success of this technology.

KEYWORDS: Nuclear technology, radiation, induced mutation, genetic diversity, genetic stability, plant breeding, dose, gamma rays, ion beam

1.1 INTRODUCTION

With the increase in the world's population, the demand for food is also rising rapidly. According to the estimate of the Food and Agriculture Organization of the United Nations (FAO), by 2050, agricultural production will need to increase by nearly 70% to meet the nutritional needs of the world's population. This challenge, combined with climate change, water scarcity, soil degradation, and the increase of diseases and pests, has made plant breeding an urgent necessity for sustainable agriculture. (FAO, 2012)

Conventional plant breeding has been carried out by humans for thousands of years through the selection and propagation of superior crops. These methods are based on natural mutations and the recombination of genes during sexual reproduction. While conventional breeding has achieved considerable successes, its limitations are also evident: it is time-consuming (often 10–15 years or more), has limited genetic diversity, and requires extensive agricultural land for the selection of desirable traits. (Bado et al., 2015)

In the early twentieth century, the discovery of the mutagenic effects of X-rays by Müller (1927) opened a new horizon for plant breeding. Since this discovery, induced mutation through radiation has become a powerful tool for plant breeding. According to the FAO/IAEA Mutant Variety Database, as of 2024, more than 3,460 mutant varieties have been registered for more than 226 crop species. (Müller, 1927; FAO/IAEA,2024)

This review article considers the evaluation of the application of nuclear technology in plant breeding, specifically the analysis of radiation effects on genetic diversity and stability. The article attempts to examine the scientific foundations, practical aspects, and future possibilities of this technology in order to provide a scientific framework for plant breeders, agricultural policy makers, and the development of Afghanistan's agricultural sector.

2. MATERIALS AND METHODS

2.1 Research Methodology and Procedure

This study was conducted in the form of a review article. The research methodology comprises the following stages:

• Data collection method: Use was made of information sources including scientific articles, books, FAO/IAEA reports, and international scientific journals. Keywords such as "radiation breeding," "mutation breeding," "gamma rays," "ion beams," "genetic diversity," "genetic stability," and "plant breeding" were used for data collection.

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• Data analysis method: Thematic analysis was employed for the analysis of the collected data. The information was organized based on various themes such as types of radiation, dose determination, types of mutations, and genetic diversity and stability.
• Data quality assessment: To assess the quality of the data, criteria including the scientific credibility of the sources, year of publication, and quality of research methodology were applied. Particular attention was given to articles published after 2015.
• Research limitations: This study is in the form of a review article and does not include the conduct of laboratory or field experiments for the collection of empirical data. This study is based on the existing scientific literature.

2.2 Research Tools and Materials

The following tools and materials were used for this review article:
• Information source databases:
– ScienceDirect
– PubMed Central (PMC)
– SpringerLink
– PLOS ONE
– FAO/IAEA Mutant Variety Database (http://mvd.iaea.org)
– Journals of the Academy of Sciences of Afghanistan
• Data analysis tools:
– Use of tables and graphs for data organization
– Reference management software for citation management
• Research materials:
– More than 50 scientific articles and reports
– Reports of international organizations (FAO, IAEA, WHO)
– Foundational books on plant breeding and genetics

3. ANALYSIS OF THE RESEARCH THEMES

3.1 Fundamental Concepts of Plant Breeding

Plant breeding is the collection of techniques that generate new varieties possessing desirable traits through the modification of the genetic structure of plants. Plant breeding can be carried out through three fundamental methods:
First: The selection method. This method selects plants possessing desirable traits by utilizing existing genetic diversity and propagates them over generations. This is the oldest and simplest method of plant breeding. (Acquaah, 2012; Priyadarshan, 2019)
Second: The hybridization method. This method generates a new genetic combination through sexual reproduction between two or more different parents. This method can create a combination of desirable traits; however, it requires a long time and extensive agricultural land.
Third: The mutation method. This method generates new genetic diversity through sudden changes in the structure of genetic material. The mutation method can be carried out through natural mutations or induced mutations. (Acquaah, 2012; Priyadarshan, 2019)

3.2 Limitations of Conventional Breeding Methods and Approaches

The limitations of conventional breeding methods can be summarized in the following points:
• Limitation of genetic diversity. Due to thousands of years of selection and propagation, the genetic base of many crop varieties has become narrow. This phenomenon reduces the ability of plants to cope with diseases, pests, and climate change. (FAO, 2010; Khoury et al., 2022).
• Length of time. Developing a new variety through conventional breeding often requires 10–15 years or more. This is too long for urgent challenges such as climate change and the emergence of new disease strains. (Acquaah, 2012; Collard & Mackill, 2008)
• Requirement of agricultural land. Conventional breeding requires large agricultural lands to cultivate a sufficient number of plants for the evaluation of different generations. (Acquaah, 2012)
• Difficulty in selecting desirable traits. In conventional breeding, the selection of desirable traits requires many generations and extensive agricultural land. (Collard & Mackill, 2008)

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3.3 Modern Methods and Approaches

Considering the limitations of conventional methods, modern methods have been developed that make plant breeding faster and more effective: (Acquaah, 2012; Bado et al., 2015)

• Induced mutation method. This method induces changes in the structure of genetic material through physical (radiation), chemical (such as EMS, NaN3), or biological (such as transposons) agents. This method can generate new sources of genetic diversity in a short period of time. [FAO], 2009; Shu, Forster, & Nakagawa, 2012)

• Molecular marker methods. These methods are used to select plants carrying desirable traits at the DNA level. These methods can make the selection process faster and more precise. (Collard & Mackill, 2008).

• Gene editing methods. Such as CRISPR-Cas9, can precisely induce changes in specific regions of the genetic material. These methods are more precise than conventional and induced mutation methods. (Jinek et al., 2012)

3.4 Radiation Breeding Methods

The radiation breeding method is a type of induced mutation that induces changes in the structure of genetic material through physical radiation. This method has the following characteristics:

• Types of radiation. Various types of radiation such as X-rays, gamma rays, neutrons, and ion beams are used for plant breeding. Each type of radiation has its specific mechanism of action and penetration capability.

• Scope of application. The radiation breeding method is applied to seeds, various plant parts (such as leaves, shoots, roots), and in vitro cultures. This method is more suitable for plants that are propagated through sexual reproduction or those that face difficulties in sexual reproduction. Ma et al., 2021; Spencer-Lopes et al., 2018)

• Level of success. According to FAO/IAEA data, radiation breeding is the most widely used induced mutation method. Globally, out of more than 3,460 registered mutant varieties, the majority have been developed through gamma rays. (FAO/IAEA, 2024.; Ma et al., 2021)

3.5 Nuclear Technology and Its Mechanism of Application in Plant Breeding

Nuclear technology is the branch of science and technology that utilizes the properties, transformations, and energy of the atomic nucleus for the benefit of humanity. The foundation of nuclear technology is based on the principles of atomic physics, and today it has widespread application in agriculture, medicine, industry, energy production, environmental protection, and scientific research. Nuclear technology is considered one of the important scientific achievements of the twentieth century and has played a significant role in the advancement of humanity. (FAO & IAEA, 2021)

In this context, the purpose of nuclear technology is not solely the production of nuclear energy, but also the techniques that utilize the principles of atomic and nuclear physics for agriculture, biology, and plant breeding.

Table 1. The most important sources of radiation in plant breeding are

Radiation/Technique	Characteristic	Application in Plant Breeding
Gamma rays	High penetration, common use	Seeds, cuttings, buds, and tissue
X-rays	Machine-generated	Induced mutation
Ion beams	High LET, relatively specific effect	Specific genetic modifications
Neutrons	High-energy particles	DNA and chromosomal alterations
Space radiation	Complex space conditions	Exploratory and experimental breeding

Gamma rays and X-rays are the most well-known approaches in classical radiation mutation breeding, whereas ion beams and other particles constitute a part of modern radiation breeding.

Nuclear technology is applied in plant breeding to induce changes in genetic material through the use of radiation. The fundamental

3.6 mechanism of this technology comprises the following stages:

First stage: Absorption of radiation. When radiation is applied to plant tissues or seeds, it collides with the atoms of the cells and absorbs energy. This energy causes ionization or excitation of the cellular molecules, particularly DNA. (Gill et al., 2015; Kim et al., 2019)

Second stage: DNA damage. The energy of radiation can induce various types of damage in the DNA structure, including single-

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strand breaks, double-strand breaks, DNA-protein cross-links, formation of oxidized bases, and formation of a basic sites.
Third stage: DNA repair or mutation. The cell's DNA repair mechanisms attempt to repair the damage. If the repair fails or is performed improperly, mutations occur. These mutations can lead to changes in gene function, changes in protein structure, or changes in chromosome structure. (Gill et al., 2015; Kim et al., 2019)
Fourth stage: Mutant generations. Plants or seeds treated with radiation are referred to as the M1 generation. M1 generation plants may exhibit signs of mutations; however, their mutations are often recessive and become apparent in the M2 or M3 generations. In order to accurately identify mutants, the evaluation of multiple generations (M1–M3) is essential. (Spencer-Lopes et al., 2018; IAEA, 2000)

3.7 Radiations Used in Plant Breeding and Their Mechanisms of Action

The radiations used for plant breeding are divided into two main groups:
First group: Low LET radiations. These radiations have Low Linear Energy Transfer (LET). Radiations in this group include:
• X-rays: They are part of the electromagnetic spectrum generated by the production of electric fields. X-rays have relatively low penetration in plant tissues and are more suitable for surface tissues.
• Gamma rays: They are generated through nuclear decay (such as Cobalt-60 or Cesium-137). Gamma rays have higher energy than X-rays and penetrate more deeply into plant tissues. These radiations are the most widely used radiations for plant breeding. (Ma et al., 2021; EFSA Panel on Genetically Modified Organisms [GMO] et al., 2021)
Second group: High LET radiations. These radiations have High Linear Energy Transfer (LET). Radiations in this group include:
• Neutrons: They are generated through nuclear reactors. As uncharged particles, neutrons penetrate deeply into plant tissues and cause more complex damage in the DNA structure.
• Ion beams: They are generated through particle accelerators. Ion beams can carry ions of various elements (such as carbon, nitrogen, argon). Due to high LET, these radiations cause more concentrated damage in the DNA structure, which leads to a higher rate of mutation. (Ma et al., 2021; Tanaka, 2009)
In terms of mechanism of action, low LET radiations cause more dispersed damage, whereas high LET radiations cause more concentrated damage. This phenomenon causes high LET radiations to induce more complex mutations compared to low LET radiations. (Ma et al., 2021; Kazama et al., 2020)

Table 2. Comparison of important types of radiation in plant breeding

Type of Radiation	Physical Characteristic	Potential Biological Effect	Important Limitation
Gamma rays	Ionizing electromagnetic radiation	DNA damage and mutations	Variation depending on dose and plant sensitivity
X-rays	Ionizing electromagnetic radiation	Induction of genetic changes	Requires evaluation of dose and energy conditions
Neutrons	Uncharged nuclear particles	Genetic damage through nuclear interactions	Specific conditions for source and radiation quality
Protons and heavy particles	Fast charged particles	Specific patterns of energy transfer	Requires specialized equipment and control
UV rays	Part of the electromagnetic spectrum	DNA damage and cellular responses	Limitations of wavelength and penetration

Source: Analytical table based on the studies of Shu et al. (2012), Nisa et al. (2019), and Xu et al. (2021)

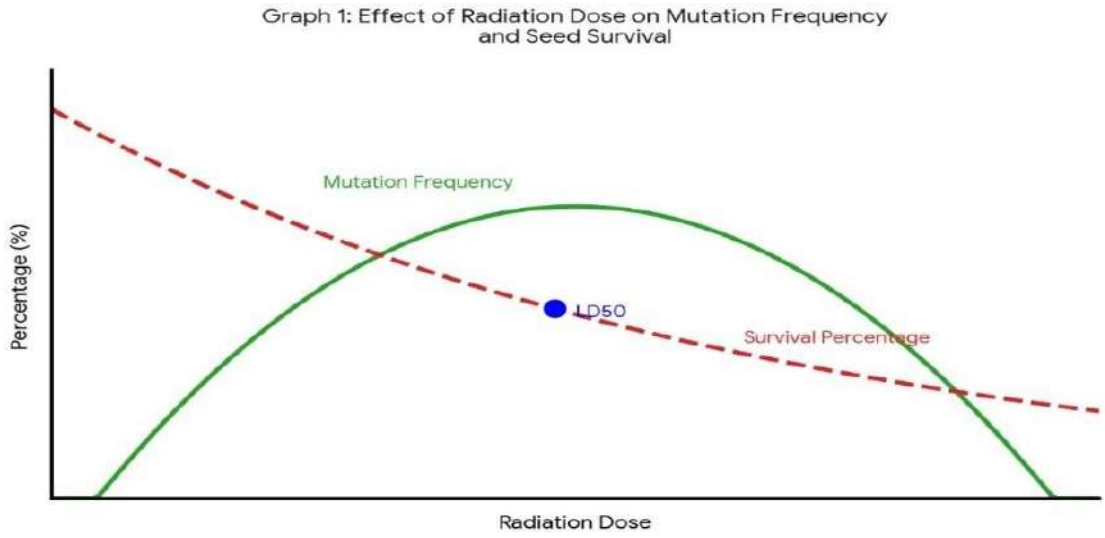
3.8 Radiation Dose and the Process of Determining the Appropriate Dose

Radiation dose is one of the important factors in plant breeding. Dose determination depends on factors such as the type of radiation, the plant species, the duration of radiation application, and the physiological condition of the plants. (Spencer-Lopes et al., 2018; EFSA Panel on Genetically Modified Organisms [GMO], 2021)

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3.9 Key criteria for dose determination:

• LD50 (Median Lethal Dose): The dose that causes the death of 50% of the plants. This dose is one of the important criteria for evaluating radiation sensitivity. For most crops, a dose around the LD50 is considered optimal for a high rate of mutation.
• GR50 (Median Growth Reduction Dose): The dose that causes a 50% reduction in growth. This criterion is more precise than LD50 because it evaluates based on growth rather than plant survival.
• LD25 and LD75: These doses cause 25% and 75% mortality, respectively. These criteria are used for more precise dose determination. (Riviello-Flores et al., 2022; Von Well et al., 2023)



Graph 1: Effect of Radiation Dose on Mutation Frequency and Seed Survival

This graph illustrates the relationship between radiation dose, plant survival, and mutation frequency, explaining how the optimal dose is determined for mutation breeding:
Red Dashed Line (Plant Survival): Shows that as the radiation dose increases, the survival rate of the plants decreases exponentially.
Green Solid Line (Mutation Frequency): Indicates that the mutation rate increases with the dose up to a certain point (the peak of the curve), after which it declines due to excessive cellular damage and lethality.
Blue Dot (Optimal Dose): Located at the intersection of high mutation frequency and acceptable survival rate (often near the LD50 or GR50). This is the ideal dose for inducing the maximum number of desirable mutations while ensuring the plants can survive and reproduce.

3.10 The Process of Determining the Appropriate Dose:

First, an assessment of radiation sensitivity is conducted for the plant species. This assessment is carried out through preliminary experiments that evaluate plant survival, growth, and physiological responses at various doses.
Second, the LD50 and GR50 values are determined through the dose-response curve. This curve illustrates the relationship between plant response and various doses.
Third, for a high mutation rate, a dose around the LD50 or GR50 is selected. However, it should be taken into consideration that the application of excessively high doses may lead to undesirable mutations and a reduction in plant survival. (Von Well et al., 2023)
Fourth, the timing of dose application and the physiological condition of the plants (such as seed moisture, temperature, and plant age) must be taken into account, as these factors can alter the magnitude of radiation effects. (Spencer-Lopes et al., 2018; Riviello-Flores et al., 2022)

3.11 Plant DNA, Radiation Damage to DNA Structure, and the Mechanism of Action

Plant DNA Structure: Plant DNA is composed of deoxyribonucleic acid (DNA), which takes the form of a chain of nucleotides. This chain consists of two polynucleotide strands that are linked together by hydrogen bonds. The DNA structure contains four

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types of bases (adenine, thymine, guanine, and cytosine). Plant DNA is located in the cell nucleus, mitochondria, and chloroplasts.(Alberts et al., 2015; Kim et al., 2019)

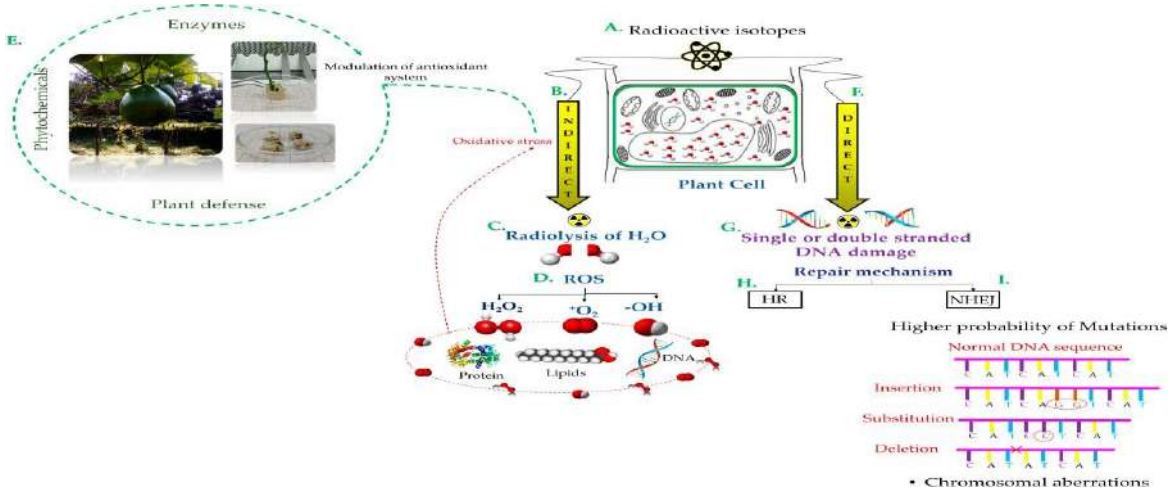


Figure 2: Plant DNA Structure (Riviello-Flores et al, 2022)

Figure 2: This figure illustrates the cellular and molecular mechanisms of radiation-induced damage in plant cells and the subsequent biological responses.

Radioactive isotopes (A) emit gamma radiation (B) that penetrates the plant cell, causing damage through two primary pathways:

1. Direct Action: Radiation directly induces single- or double-stranded DNA damage (G).
2. Indirect Action: Radiation causes the radiolysis of water (C), generating reactive oxygen species (ROS) (D). These ROS induce oxidative stress (E), which leads to the peroxidation of lipids, damage to proteins, and further DNA damage.

To counteract this, the plant activates two main defense mechanisms:

DNA Repair Mechanisms (H): Including Homologous Recombination (HR) and Non-Homologous End Joining (NHEJ).
Physiological Defenses (E): Modulating the antioxidant system by activating enzymes and plant defense mechanisms.

If the DNA damage is not accurately repaired, it results in a higher probability of mutations (I), specifically insertions, substitutions, and deletions within the DNA sequence, as well as larger chromosomal aberrations.

3.11.1 DNA Damage: Radiation energy can induce various types of damage in the DNA structure:

• Single-strand breaks: When radiation causes a break in one strand of the DNA structure. This damage is often repaired by the cell's DNA repair mechanisms.

• Double-strand breaks: When radiation causes breaks in both strands of the DNA structure. This damage is highly deleterious to the cell, as the repair process is difficult and can lead to chromosomal rearrangements or cell death. (Manova & Gruszka, 2015; Kim et al., 2019)

• DNA-protein cross-links: When radiation induces linkages between DNA and proteins. This damage can disrupt DNA replication and transcription processes.

• Formation of oxidized bases: When radiation interacts with DNA bases, causing their oxidation. This damage can lead to alterations in the DNA sequence.

• Formation of abasic sites: When radiation removes a base from the DNA. This damage can lead to the incorporation of incorrect bases during DNA replication. (Gill et al., 2015)

3.11.2 Repair Mechanisms: Plants possess various mechanisms for the repair of DNA damage:

- Base Excision Repair (BER): This mechanism is utilized for the repair of oxidized or modified bases.
- Nucleotide Excision Repair (NER): This mechanism is utilized for the repair of DNA lesions that cause distortion of the DNA structure.

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• Double-strand Break Repair: This mechanism is utilized for the repair of double-strand breaks. This repair can be carried out via homologous recombination or non-homologous end joining.

When repair mechanisms fail or perform inaccurate repair, mutations occur. These mutations can lead to alterations in gene function, changes in protein structure, or modifications in chromosome structure. (Kim et al., 2019; Manova & Gruszka, 2015)

3.12 Mutation and Types of Mutations

A mutation is defined as a sudden change in the structure of genetic material that can be transmitted from one generation to the next. Mutations can be spontaneous or induced. Spontaneous mutations arise from errors in cellular metabolism, environmental factors, or errors during DNA replication. Induced mutations are generated through physical, chemical, or biological agents. (Griffiths et al., 2015; Hartwell et al., 2015)

Types of Mutations:

First: Gene Mutation. These mutations cause an alteration in the DNA sequence within a single gene. This category includes:

• Substitution: When one base in the DNA sequence is replaced by another base. This can be either a transition (the replacement of a purine with a purine, or a pyrimidine with a pyrimidine) or a transversion (the replacement of a purine with a pyrimidine).

• Insertion/Deletion: When one or several bases are inserted into or deleted from the DNA sequence. These mutations can cause a frameshift, which leads to an alteration in protein structure. (Griffiths et al., 2015)

Second: Chromosomal Mutation. These mutations cause changes in the structure or number of chromosomes. This category includes:

• Chromosomal structural changes: Such as deletion (loss of a segment of a chromosome), duplication (doubling of a segment of a chromosome), inversion (reversal of the sequence of a segment of a chromosome), and translocation (attachment of a segment of a chromosome to another chromosome).

• Chromosomal numerical changes: Such as aneuploidy (a change in chromosome number resulting from the gain or loss of one or several chromosomes) and polyploidy (an increase in the number of chromosome sets). (Chen et al., 2014; Shu et al., 2012)

Third: Genome Mutation. These mutations cause changes in the structure of the entire genome, such as polyploidy, which is highly significant in plant breeding.

3.12.1 Induced Mutation

Induced mutation is the generation of changes in the structure of genetic material through external agents. These agents can be physical, chemical, or biological.

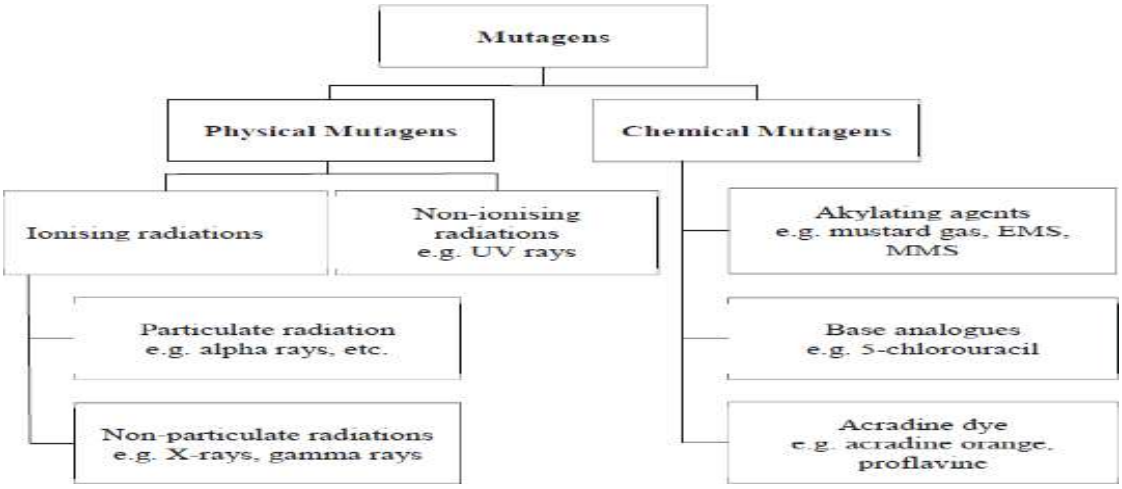


Figure 3: classification of mutagens

Figure3: The Figure is a hierarchical flowchart illustrating the classification of mutagens (agents that cause mutations). It is divided into two main categories: Physical Mutagens and Chemical Mutagens.

- Physical Mutagens are further subdivided into Ionizing radiations and Non-ionizing radiations (such as UV rays).

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Ionizing radiations are then split into Particulate radiation (e.g., alpha rays) and Non-particulate radiations (e.g., X-rays, gamma rays).

- Chemical Mutagens are classified into three groups: Alkylating agents (e.g., mustard gas, EMS, MMS), Base analogues (e.g., 5-chlorouracil), and Acridine dyes (e.g., acridine orange, proflavine).

Physical Agents: These agents include:

- Radiation: Such as X-rays, gamma rays, neutrons, ion beams, and ultraviolet (UV) radiation.
- Temperature: Sudden changes in temperature can induce mutations.

Chemical Agents: These agents include:

- Alkylating Agents: Such as EMS (Ethyl Methane Sulfonate), MMS (Methyl Methane Sulfonate), and DES (Diethyl Sulfate).
- Base Analogs: Such as 5-Bromouracil and 2-Aminopurine.
- DNA Intercalating Agents: Such as Ethidium Bromide and Acridine

Orange. Biological Agents: These agents include:

- Transposons: Segments of DNA that can relocate within the genome and cause alterations in gene function.
- Viruses: Certain viruses can induce mutations within the plant genome. (Shu et al., 2012; Spencer-Lopes et al., 2018)

3.13 Plant Genetic Diversity

Genetic diversity is the sum of variations in genetic material within a species. This diversity is a fundamental resource for plants to cope with diseases, pests, and climate change. (Govindaraj et al., 2015)

Sources of Genetic Diversity:

• Accumulation of natural mutations: Over thousands of years, natural mutations have led to an increase in genetic diversity.

• Recombination of genes during sexual reproduction: During sexual reproduction, new genetic combinations are generated through chromosomal crossing over and the independent assortment of genes. (Shu et al., 2012)

• Diversity generated through induced mutations: Diversity generated via radiation or chemical agents can create novel sources of genetic diversity. (Hajjar & Hodgkin, 2007)

Importance of Genetic Diversity:

• Resistance to diseases: Plants possessing genetic diversity are more resistant to diseases.

• Adaptation to climate change: Plants with genetic diversity can adapt better to climate change.

• Potential for yield improvement: Through genetic diversity, high-yielding varieties can be developed. (Govindaraj et al., 2015)

3.14 Effects of Radiation on Plant Genetic Diversity and Mechanisms of Action

The effects of radiation on genetic diversity are based on the following mechanisms:

First Mechanism: Increase in Mutation Rate. Radiation induces an increase in the mutation rate through the accumulation of damage in the DNA structure. These mutations can lead to alterations in gene function or changes in chromosome structure. The increase in mutation rate results in increased genetic diversity. (Spencer-Lopes et al., 2018)

Second Mechanism: Increase in Chromosomal Rearrangement. Radiation induces chromosomal structural changes (such as translocation, inversion, and duplication). These changes lead to increased genetic diversity, as they generate novel combinations of genes. (Manova & Gruszka, 2015)

Third Mechanism: Alteration of Gene Expression. Radiation can induce changes in gene expression. These changes can lead to alterations in the plant phenotype, which manifest as genetic diversity. (Kim et al., 2019)

Fourth Mechanism: Induction of Polyploidy. Radiation can induce an increase in chromosome number (polyploidy). Polyploidy can lead to increases in plant size, yield, and other desirable traits. (Chen et al., 2014)

3.14.1 Magnitude of Radiation Effects: The magnitude of radiation effects on genetic diversity depends on the type of radiation, the dose, the plant species, and environmental conditions. For example, high-LET radiation (such as ion beams) induces more complex mutations compared to low-LET radiation (such as gamma rays). (Kazama et al., 2020)

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Table 3: Relationship Between Dose, DNA Damage, Mutation Probability, Genetic Instability, and Plant Survival

Dose	DNA Damage	Mutation Probability	Genetic Instability Probability	Plant Survival
Very Low	Low	Low	Low	High
Low	Slight–Moderate	Increasing	Low–Moderate	Relatively High
Moderate/Suitable	Moderate	Selectable	Controlled	Relatively Suitable
High	Very High	Very High	High	Low
Very High	Severe	Severe Damage Rather than Beneficial Mutation	Very High	Very Low

3.15 Positive and Negative Aspects

3.15.1 Positive Aspects:

- Increase in Genetic Diversity: Through irradiation-induced increase in genetic diversity, it is possible to develop varieties possessing new desirable traits. (Ma et al., 2021; Spencer-Lopes et al., 2018)
- Time Reduction: The irradiation-based breeding method is considerably faster compared to conventional breeding.
- Generation of Novel Traits: Through irradiation, it is possible to generate traits that do not arise through natural mutations.
- Adaptation to Climate Change: Varieties developed through irradiation may exhibit resistance to drought, heat, and salinity. (Ma et al., 2021; Spencer-Lopes et al., 2018)

3.15.2 Negative Aspects:

- Induction of Unwanted Mutations: The application of radiation can lead to unwanted mutations, which result in reduced plant survival and decreased yield. (Riviello-Flores et al., 2022; Spencer-Lopes et al., 2018)

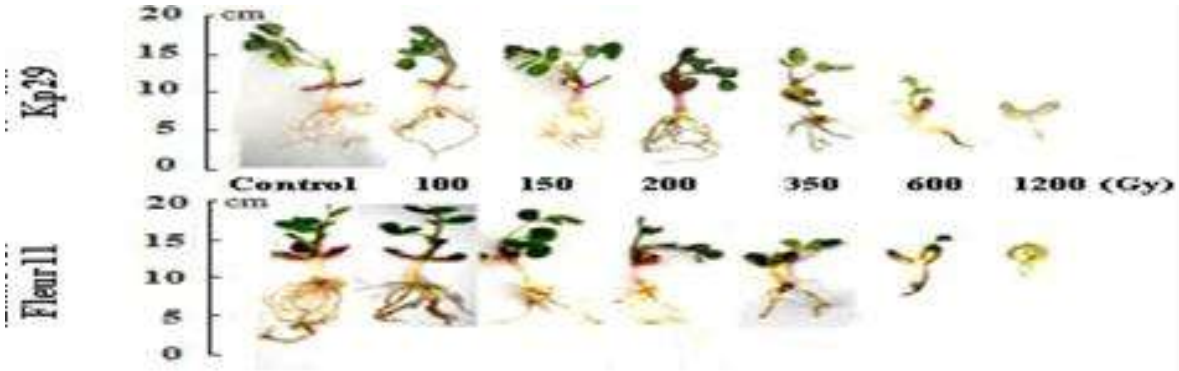


Figure4: Negative Aspects (Saibari et al,2023)

Figure4: Visual comparison of seedling growth and morphology under different gamma irradiation doses for two pea varieties, "Kp29" (top row) and "Fleur11" (bottom row). The treatments progress from left to right: Control, 100, 150, 200, 350, 600, and 1200 Gy. The image demonstrates a clear dose-dependent decline in plant growth and development. While the Control and lower doses (100 and 150 Gy) exhibit healthy shoot and root systems, higher doses cause progressive growth inhibition, root shortening, and stunting. At the highest doses (600 and 1200 Gy), severe morphological damage is evident, with minimal shoot elongation and highly restricted root development.

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3.15.2.1 Reduction in Survival Rate: The application of high doses can cause a reduction in plant survival.



Figure 5: Negative Aspects (Sankaran, Kalaivanan, & Gowda, 2021)

Figure5: Visual comparison of plant seedling growth and survival across different gamma irradiation dose treatments. The panel displays six trays, progressing from left to right: Control, 25 Gy, 50 Gy, 60 Gy, 75 Gy, and 100 Gy. The image clearly illustrates a dose-dependent decline in plant survival and vigor. While the Control and lower-dose treatments (25 Gy and 50 Gy) show dense, healthy green seedling populations, higher doses result in a drastic reduction. At 60 Gy, severe growth inhibition is visible, and at the highest doses (75 Gy and 100 Gy), seedling survival is extremely low, with mostly bare soil and very few surviving plants.

- Genetic Stability Concern: Changes induced through artificial mutations can lead to a reduction in genetic stability. (Manova & Gruszka, 2015; Shu et al., 2012)
- Requirement for Cost and Infrastructure: The application of radiation requires specific infrastructure (such as radiation-generating equipment) and the availability of professional personnel.

3.16 Genetic Stability

Genetic stability is defined as the unchanged transmission of genetic material from one generation to the next. This stability is essential for the conservation of plant varieties and the maintenance of their characteristics.
(Manova & Gruszka, 2015; Kim et al., 2019
Importance of Genetic Stability:
• Maintenance of Variety Characteristics: Genetic stability ensures that the characteristics of a variety remain constant across generations.
• Stability of Crop Production: Genetic stability is essential for the consistency of crop production.
• Disease Resistance: Genetic stability can contribute to the maintenance of resistance against diseases. (Hartwell et al., 2018; Manova & Gruszka, 2015)
Factors of Genetic Stability:
• DNA Repair Mechanisms: DNA repair mechanisms are fundamental for maintaining genetic stability.
• Chromosome Segregation Mechanism: The mechanism of proper chromosome segregation during meiosis and mitosis is essential for genetic stability.
• Stability of Environmental Conditions: Stable environmental conditions can contribute to the maintenance of genetic stability. (Manova & Gruszka, 2015; Hase et al., 2020)

3.16.1 Effects of Radiation on Plant Genetic Stability

The effects of radiation on genetic stability are as follows:
First: Reduction of Genetic Stability. Radiation induces a reduction in genetic stability by increasing damage to the DNA structure. This damage can lead to an increase in mutations, which results in decreased genetic stability. (Hoffmann & Sgrò, 2011)
Second: Increase of Variations Across Generations. Plants treated with radiation may exhibit various alterations in the M1, M2, and M3 generations. These variations can lead to a reduction in genetic stability.
Third: Induction of Unwanted Mutations. The application of radiation can lead to unwanted mutations, which result in reduced plant survival and decreased yield. These mutations can lead to a reduction in genetic stability. (Gill et al., 2015; Kim et al., 2019)

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Fourth: Increase in Chromosomal Rearrangement. Radiation induces an increase in chromosomal rearrangements. These alterations can lead to a reduction in genetic stability. (Manova & Gruszka, 2015; Hase et al., 2020)

Strategies for Maintaining Genetic Stability:

• Determining the Optimal Dose: Determining the appropriate radiation dose can help in maintaining genetic stability. (Hoffmann & Sgrò, 2011)

• Evaluation of Mutants Across Multiple Generations: The evaluation of mutants across multiple generations (M1–M3) can assist in determining genetic stability. (Shu et al., 2012; Spencer-Lopes et al., 2018)

• Use of Molecular Markers: The use of molecular markers can aid in the assessment of genetic stability. (Hoffmann & Sgrò, 2011)

3.17 The Relationship Between Genetic Diversity and Stability

The relationship between genetic diversity and stability is a complex and interactive one:

First Aspect: Diversity is essential for stability. Genetic diversity is essential for plants to cope with climate change, diseases, and other challenges. Plants possessing diversity can adapt better to environmental changes and contribute to maintaining their genetic stability. (Govindaraj et al., 2015; Hajjar & Hodgkin, 2007)

Second Aspect: Excessive diversity can reduce stability. The generation of excessive diversity can lead to a reduction in genetic stability. This phenomenon causes the characteristics of plants to fail to remain constant across generations.

Third Aspect: The need for a balance. Maintaining a balance between genetic diversity and stability is essential. This phenomenon requires plant breeders to maintain a balance between both diversity and stability through the appropriate dose and the appropriate method. (Hajjar & Hodgkin, 2007; Hoffmann & Sgrò, 2011)

Fourth Aspect: Dependence on time and space. The relationship between genetic diversity and stability depends on time and space. For example, during climate change, diversity is highly important, whereas for the stability of crop production, stability is more important. (FAO, 2019; Govindaraj et al., 2015).

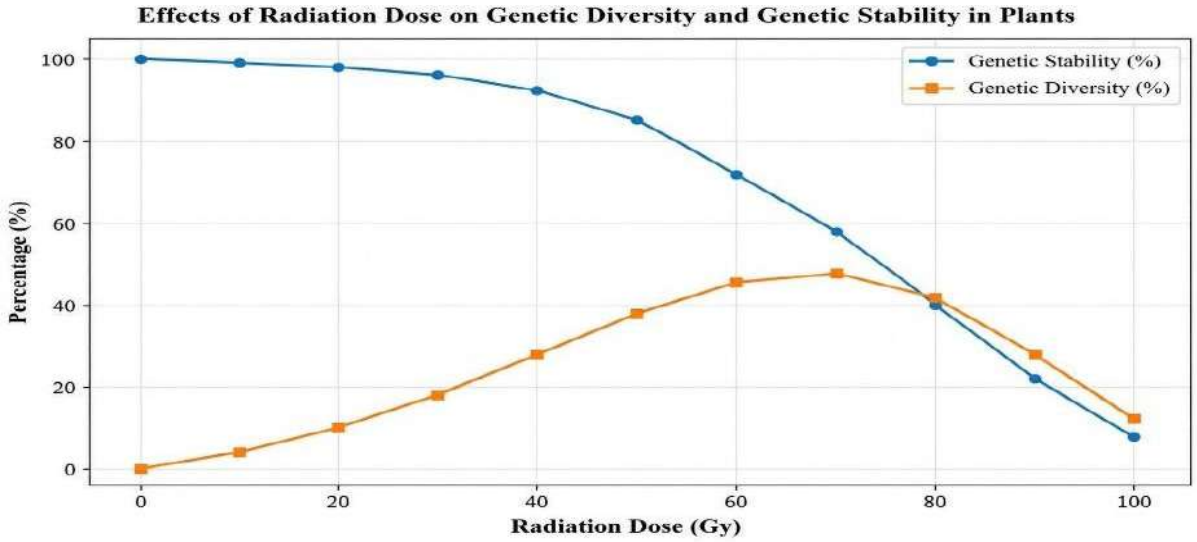


Figure 6: Relationship Between Radiation Dose, Genetic Diversity, and Genetic Stability

This graph illustrates the inverse relationship and the optimal balance between induced genetic diversity and genetic stability across varying radiation doses (Gy). The blue curve shows that genetic stability starts at 100% at 0 Gy and progressively declines as the dose increases, dropping significantly after 60 Gy and approaching near zero at 100 Gy. Conversely, the orange curve demonstrates that induced mutation/diversity starts at 0%, steadily increases with higher doses, and peaks at approximately 50% around 70 Gy. Beyond this optimal dose, the diversity curve also begins to decline, likely due to severe cellular damage. The intersecting curves highlight a critical trade-off: achieving maximum genetic diversity requires higher doses that simultaneously compromise genetic stability.

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3.18 Importance of Genetic Stability and Diversity

Importance of Genetic Diversity:

• For Food Security: Through genetic diversity, it is possible to develop new varieties with high yield, disease resistance, and adaptability to climate change.

• For Sustainable Agriculture: Through genetic diversity, new varieties essential for sustainable agriculture can be developed. (Govindaraj et al., 2015; Swarup et al., 2021).

• For Biological Diversity: Genetic diversity is an important component of biological diversity and is essential for ecosystem stability. (FAO, 2019)

Importance of Genetic Stability:

• Maintenance of Variety Characteristics: Through genetic stability, the characteristics of varieties can be maintained constant across generations.

• Stability of Crop Production: Through genetic stability, the stability of crop production can be ensured. (Spencer-Lopes et al., 2018)

• Disease Resistance: Through genetic stability, it can assist in maintaining resistance against diseases (Swarup et al., 2021)

Table 4: Comparison Between Genetic Stability and Genetic Diversity

Genetic Stability	Genetic Diversity
Maintains existing traits	Generates new traits
Ensures consistency across generations	Increases adaptability
Reduces undesirable changes	Increases the potential for beneficial changes

3.19 Advantages and Limitations of Nuclear Technology in Plant Breeding

3.19.1 Advantages

- Increased Genetic Diversity: Radiation can be used to generate new sources of genetic diversity by inducing mutations in plant genetic material.
- Reduced Breeding Time: Mutation induction through radiation can accelerate the development of desirable plant traits and complement conventional plant-breeding methods, although the overall breeding process may still require several generations of selection and evaluation.
- Development of Novel Traits: Radiation-induced mutagenesis can generate new genetic variations and desirable traits that may not be readily available in existing varieties or conventional breeding populations. (Shu et al., 2012; Spencer-Lopes et al., 2018)
- Adaptation to Climate Change: Radiation-induced mutants may exhibit improved tolerance to environmental stresses, including drought, high temperatures, and soil salinity, depending on the plant species and the mutations induced. (Ma et al., 2021; Spencer-Lopes et al., 2018)
- Availability of International Experience: The application of radiation-induced mutation breeding in numerous countries provides opportunities for international collaboration, knowledge exchange, and the sharing of successful breeding practices. (FAO & IAEA, 2018)

3.19.2 Limitations

- Induction of Undesirable Mutations: Radiation may induce undesirable mutations that negatively affect plant growth, survival, fertility, and yield, necessitating the screening and elimination of unsuitable mutants. (Ma et al., 2021; Spencer-Lopes et al., 2018)
- Concerns Regarding Genetic Stability: Radiation-induced mutations may sometimes be associated with unintended genetic changes or unstable traits. Therefore, the genetic stability and heritability of selected mutants should be evaluated over successive generations.
- Costs and Infrastructure Requirements: The application of radiation-based mutation breeding requires specialized infrastructure, such as radiation-generating equipment and irradiation facilities, as well as trained personnel, appropriate safety measures, and adequate financial resources. (Manova & Gruszka, 2015)

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- Challenges in Determining the Appropriate Radiation Dose: The optimal radiation dose depends on several factors, including the type of radiation, plant species, genotype, biological material, and experimental conditions. Consequently, preliminary dose-response studies are often necessary to identify suitable irradiation levels. (Riviello-Flores et al., 2022; Von Well et al., 2023)
- Limited Public Awareness: Insufficient public understanding of nuclear technology and radiation-induced mutation breeding may create misconceptions and barriers to the adoption of this technology. Effective scientific communication and public education can help address these challenges. (IAEA, 2014)

Table 5: Potential Benefits and Limitations of Radiation-Induced Mutation Breeding

Aspect	Potential Benefit	Potential Limitation
Genetic Diversity	Generates new genetic variations	Not all induced mutations are beneficial
Breeding Efficiency	Provides additional genetic variation for selection	Multiple generations and considerable time may be required to identify desirable plants
Improvement of Desirable Traits	Enables selection for specific desirable characteristics	Undesirable traits may also arise
DNA Alterations	Serves as a source of genetic variation	May cause genetic damage and cell death
Genetic Stability	Desirable mutations can potentially be stabilized through selection	Evaluation over multiple generations is required
Technical Application	Can be incorporated into plant-breeding programs	Requires specialized equipment, trained personnel, and radiation safety measures

3.20 The Role of International Organizations in Nuclear Technology-Based Plant Breeding

3.20.1 Food and Agriculture Organization of the United Nations (FAO)

The Food and Agriculture Organization of the United Nations (FAO) plays an important role in promoting the application of nuclear technology in plant breeding as part of its global efforts to improve agricultural productivity and food security. The organization supports member countries through technical assistance, capacity-building and training programs, and platforms for information sharing and international knowledge exchange.

3.20.2 International Atomic Energy Agency (IAEA)

The International Atomic Energy Agency (IAEA) plays a significant role in promoting the peaceful application of nuclear technology, including the use of radiation-induced mutagenesis in plant breeding. The agency assists member countries in developing relevant technical infrastructure, training specialized personnel, and supporting research projects aimed at developing improved crop varieties and strengthening agricultural resilience. (IAEA, 2020)

3.20.3Joint FAO/IAEA Programme

The Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture provides an important framework for international cooperation in the application of nuclear techniques to plant breeding and agricultural development. Through its research, technical cooperation, and capacity-building activities, the joint programme supports mutation breeding and the development of improved crop varieties. It also maintains the IAEA Mutant Variety Database (MVD), which documents officially released crop varieties developed through induced mutation and related breeding approaches worldwide. (IAEA/FAO, 2024).

3.21 Role of International Research Centers

Research centres and agricultural institutions in various countries contribute significantly to the advancement of nuclear technology in plant breeding. These institutions conduct research on radiation-induced mutagenesis, evaluate genetic variation, identify desirable traits, and develop improved crop varieties with characteristics such as higher yield, disease resistance, and tolerance to environmental stresses. Their scientific findings and practical experiences can serve as valuable models for other countries seeking to strengthen their plant-breeding programs and agricultural research capacity. (IAEA, 2020)

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3.21.1Analytical Framework of the Roles of FAO and IAEA

The roles of the Food and Agriculture Organization of the United Nations (FAO) and the International Atomic Energy Agency (IAEA) in promoting nuclear technology for plant breeding can be summarized as follows (IAEA/FAO, 2024).

Table 6: Analytical Framework of the Roles of FAO and IAEA in Nuclear Technology-Based Plant Breeding. (IAEA/FAO, 2024).

Area	Role of FAO/IAEA
Research	Conducting and supporting applied research in mutation breeding and agricultural improvement
Irradiation	Providing technical support and irradiation services for mutation induction
Dosimetry	Measuring, monitoring, and controlling radiation doses to ensure accurate and reproducible irradiation treatments
Training	Strengthening the technical capacity and professional skills of researchers and specialists
Coordinated Research Projects (CRPs)	Promoting international collaborative research and scientific knowledge exchange
Technology	Facilitating technology transfer and the adoption of advanced nuclear techniques in agriculture
Biotechnology	Integrating molecular and genomic methods to characterize mutations and evaluate genetic variation
Information	Maintaining the Mutant Variety Database (MVD), which documents officially released mutant crop varieties
Agriculture	Supporting the practical application and adoption of improved crop varieties
Climate Resilience	Promoting the development of climate-resilient crops with improved tolerance to environmental stresses
Food Security	Supporting agricultural productivity, crop quality, and sustainable food security

3.21.2 Analytical Overview

The joint FAO/IAEA programme plays an important role in advancing the peaceful application of nuclear techniques in agriculture. Its official mandate includes supporting applied research, facilitating technology transfer, strengthening national capacities, and providing technical assistance and policy advice to member countries. Through these activities, the programme contributes to the development of improved crop varieties, the effective use of radiation-induced mutagenesis, and the promotion of sustainable agricultural production and food security.

3.22 The Importance of Nuclear Technology for Afghanistan

As an agricultural country, Afghanistan relies heavily on agriculture and livestock production as important components of its economy. However, the country faces numerous agricultural challenges, including drought, soil degradation, low crop yields, and the increasing incidence of crop diseases and pests. The application of nuclear technology, particularly radiation-induced mutation breeding, could offer several potential benefits for Afghanistan's agricultural sector. (World Bank, 2025)

First: Development of Drought-Tolerant Crop Varieties

Radiation-induced mutation breeding can help develop crop varieties with improved drought tolerance. Such varieties could be particularly valuable in Afghanistan, where recurrent droughts and water scarcity pose significant challenges to agricultural productivity and food security. (FAO, 2025)

Second: Development of High-Yielding Crop Varieties

The application of radiation-induced mutagenesis can generate genetic variation that enables plant breeders to select and develop high-yielding crop varieties. Improving crop productivity is essential for strengthening Afghanistan's food security, increasing agricultural output, and improving farmers' livelihoods.

Third: Development of Disease-Resistant Crop Varieties

Radiation-induced mutation breeding can contribute to the development of crop varieties with improved resistance to plant diseases. This approach may help reduce crop losses, improve agricultural productivity, and strengthen the resilience of Afghanistan's farming systems. The success of such efforts depends on identifying and evaluating beneficial mutations under local growing conditions.

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Fourth: Benefiting from International Experience

Afghanistan can benefit from the scientific knowledge, research findings, and practical experience of countries such as Pakistan, Iran, China, and Japan, which have conducted research and developed applications in mutation breeding and agricultural biotechnology. International collaboration could facilitate knowledge exchange, technical cooperation, and the adaptation of successful approaches to Afghanistan's agricultural conditions. (IAEA, 2024)

Fifth: Human Resource Development and Capacity Building

The effective application of nuclear technology in plant breeding requires trained specialists, qualified researchers, and appropriate technical expertise. Training programs, academic collaboration, and specialized research opportunities could strengthen Afghanistan's scientific and technical capacity and support the long-term development of its agricultural sector.

Sixth: Support from International Organizations

International organizations, particularly the Food and Agriculture Organization of the United Nations (FAO) and the International Atomic Energy Agency (IAEA), could support Afghanistan in applying nuclear techniques to agricultural development. Such support may include technical assistance, professional training, research collaboration, technology transfer, and, where available, financial or project-based assistance to strengthen national research capacity.

3.22.2 Concluding Remarks

The application of nuclear technology in plant breeding offers potential opportunities to address some of Afghanistan's major agricultural challenges. Through the development of improved crop varieties, investment in human resource capacity, and cooperation with international research institutions, Afghanistan could strengthen crop productivity, improve resilience to environmental stresses, and contribute to long-term food security. However, successful implementation would require appropriate research infrastructure, radiation safety measures, locally adapted breeding programs, and systematic evaluation of the genetic stability and agronomic performance of newly developed varieties.

4. RESULTS AND FINDINGS

This review article presents the following results and findings:

Overall, the findings of this review study demonstrate that nuclear technology, particularly induced mutation through ionizing radiation, represents an important scientific and practical tool for generating novel genetic diversity in plant breeding. Radiation induces changes at the DNA and genome levels, thereby providing new genetic materials for breeding purposes. This genetic variability can be exploited to develop improved plant varieties with higher yields, superior quality, enhanced disease resistance, and greater tolerance to environmental stresses.

At the same time, radiation dose must be carefully optimized, as it plays a critical role in determining the relationship between mutation frequency and DNA damage. Therefore, determining plant radio sensitivity, selecting an appropriate radiation dose, screening large mutant populations, and evaluating desirable traits over several generations are fundamental requirements for successful mutation breeding.

Finally, from the perspective of this study, genetic diversity is considered the primary source of breeding innovation, whereas genetic stability constitutes the foundation for the persistence and reliability of improved traits. Accordingly, future plant breeding programs should integrate radiation-induced mutation techniques with molecular markers, genomics, advanced screening methods, and other modern biotechnological tools to improve the efficiency and precision of crop improvement.

Finding 1: Effectiveness of Radiation-Induced Mutation Breeding

Radiation-induced mutation breeding is an effective and valuable method for increasing genetic diversity, generating new desirable traits, and potentially accelerating the development of improved crop varieties. According to FAO/IAEA data, by 2024, more than 3,460 mutant varieties derived through induced mutagenesis had been documented across more than 226 crop species.

Finding 2: Importance of Selecting the Appropriate Radiation Dose.

The selection of an appropriate radiation dose is one of the most important factors determining the success of radiation-induced mutation breeding. The median lethal dose (LD_{50}) and the growth reduction dose (GR_{50}) are commonly used criteria for determining suitable irradiation levels. Excessively high radiation doses may cause undesirable mutations, severe biological damage, and reduced plant survival, whereas doses that are too low may fail to generate sufficient useful genetic variation for effective selection.

Finding 3: Differences in the Mechanisms of Radiation Action

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Different types of radiation act through distinct mechanisms and produce different patterns of DNA damage. Low linear energy transfer (LET) radiation, such as gamma rays, generally produces more sparsely distributed ionization events, whereas high-LET radiation, such as ion beams, produces more densely concentrated ionization along particle tracks. These differences can influence the types and complexity of mutations generated, with high-LET radiation potentially inducing more complex DNA alterations.

Finding 4: The Relationship Between Genetic Diversity and Genetic Stability

There is a complex relationship between genetic diversity and genetic stability. Genetic diversity is essential for enabling plants to respond to climate change, diseases, pests, and other environmental challenges. In contrast, genetic stability is important for maintaining desirable varietal characteristics and ensuring consistent agricultural performance across generations. Therefore, maintaining an appropriate balance between genetic diversity and genetic stability is essential for successful plant-breeding programs.

Finding 5: The Role of International Organizations and Research Centres

International organizations, particularly the Food and Agriculture Organization of the United Nations (FAO) and the International Atomic Energy Agency (IAEA), together with international agricultural research centres, play a crucial role in promoting radiation-induced mutation breeding and facilitating the exchange of scientific knowledge and practical experience. Their technical assistance, training programmes, research collaboration, and technology-transfer initiatives can help developing countries establish and strengthen their mutation-breeding capabilities. (IAEA/FAO, 2024)

Finding 6: The Importance of Nuclear Technology for Afghanistan

The application of radiation-induced mutation breeding is potentially important for Afghanistan because the country faces major agricultural challenges, including recurrent drought, soil degradation, and low crop productivity. Through appropriate research programmes, radiation-induced mutation breeding could provide opportunities to develop crop varieties with improved yield potential and enhanced tolerance to environmental stresses. Consequently, this technology could contribute to the modernization of Afghanistan's agricultural sector, improved food security, and more sustainable agricultural development. (IAEA/FAO, 2024)

5. DISCUSSION

The findings of this review article indicate that the application of nuclear technology, particularly radiation-induced mutagenesis, represents a powerful tool for plant breeding. This technology can generate new sources of genetic diversity and facilitate the development of desirable plant traits, complementing conventional breeding methods and potentially improving the efficiency of crop improvement programmes.

Importance of Radiation Types

The findings of this review indicate that different types of radiation produce different biological effects. Gamma rays have been widely used in plant mutation breeding because of their established applications, the availability of well-calibrated irradiation facilities, and extensive international research experience. However, high-linear-energy-transfer (high-LET) radiation, such as ion beams, can induce more complex mutations and may be particularly suitable for certain specific breeding objectives.

Challenges in Radiation Dose Selection

Determining the appropriate radiation dose remains a major challenge in the successful application of radiation-induced mutation breeding. Dose selection depends on several factors, including the type of radiation, plant species, irradiation duration, and physiological condition of the plant material. The median lethal dose (LD_{50}) and the growth reduction dose (GR_{50}) are commonly used to guide the selection of suitable irradiation levels. However, these parameters must be determined and adjusted according to the specific plant species, genotype, and experimental conditions.

Balancing Genetic Diversity and Genetic Stability

Maintaining an appropriate balance between genetic diversity and genetic stability represents a complex challenge in plant breeding. Increased genetic variation may introduce undesirable mutations or reduce the uniformity of selected plant populations, whereas excessive genetic uniformity may limit the available variation needed for future improvement and adaptation. Therefore, plant breeders must select useful mutations while ensuring that desirable traits remain stable and heritable across successive generations.

Specific Considerations for Afghanistan.

For Afghanistan, the application of nuclear technology in plant breeding could serve as an important tool for agricultural development. However, its successful implementation would require the establishment of appropriate research infrastructure, the

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training of qualified personnel, and support from international organizations. In particular, the development of drought-tolerant, high-yielding, and disease-resistant crop varieties would be highly valuable for Afghanistan's agricultural sector. These efforts could help address recurrent drought, crop losses, and other challenges affecting agricultural productivity and food security.

6. CONCLUSION

In conclusion, nuclear technology, particularly radiation-induced mutagenesis, is a valuable tool for plant breeding that can be used to increase genetic diversity, generate new desirable traits, and potentially accelerate crop improvement. This technology is especially relevant to countries facing challenges such as climate change, recurrent drought, and increasing pressure from plant diseases and pests.

The successful application of this technology depends on selecting appropriate radiation types and doses, maintaining a suitable balance between genetic diversity and genetic stability, and systematically evaluating the performance of selected mutants. Furthermore, support from international organizations, the training of qualified personnel, and the development of appropriate research infrastructure are fundamental requirements for effective implementation.

For Afghanistan, radiation-induced mutation breeding could contribute significantly to agricultural development, improved food security, and increased crop productivity. Nevertheless, realizing these potential benefits will require long-term planning, international cooperation and assistance, investment in scientific and technical capacity, and sustained national commitment. With appropriate research programmes and systematic evaluation under local agricultural conditions, this technology could become a useful component of Afghanistan's broader strategy for sustainable agricultural development.

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