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Mutation Breeding and Its Importance in Modern Plant Breeding

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Abstract: Mutations occur as a result of alterations in DNA or during the replication/cell division process. For agricultural development, plant breeding necessitates genetic variety of valuable features. Multiple mutant alleles, on the other hand, constitute a source of genetic variety for crop breeding and, in many cases, functional investigation of the targeted gene. Plant breeding can only improve when the breeder has access to enough variation for a particular trait. Any change in an organism's DNA that is not caused by normal recombination and segregation is referred to as a mutation. Exposure to mutagenic agents such as radiation or certain chemicals, as well as faults made during normal cell division and replication, are all possible causes. The first breeding successes were achieved by utilizing spontaneous (naturally occurring) mutations. The most well-known example is the use of semi-dwarf wheat and rice mutants during the 'Green Revolution.' Induced mutagenesis is becoming increasingly popular in plant molecular biology as a method for identifying and isolating genes, as well as studying their structure and function. Molecular mutation breeding is ushering in a new era of crop enhancement mutation breeding. In the coming years and decades, mutation breeding will play a vital role in crop improvement and resolving concerns related to global food security. As a result, the goal of this review paper is to evaluate the function of mutant breeding in crop development and how it might be used.

Keywords: Mutation, Plant Breeding, Crop Improvement, Mutagenesis

1. Introduction

Human population is now expanding at a rapid rate, with an estimated 9 billion people on the planet by 2050 [19]. This will result in food scarcity on the planet. To meet the rising demand for food and proper nutrition, improvements in food production are urgently needed. Crop genetic enhancement is a critical component of attempts to solve global food security and nutrition issues [30]. For agricultural development, plant breeding necessitates genetic diversity of beneficial features [16].

Mutation, or a heritable change in an organism's genetic feature, is a natural process that produces new gene variants (alleles). All genetic changes in any organism, including plants, are mostly due to mutation [37]. Mutagenic agents, like as radiation and certain chemicals, can then be employed to cause mutations and generate genetic variants from which desired mutants can be chosen [45]. Mutation produces variation, which is used by natural selection and is a driving force in evolution [29].

Plant breeding, especially mutant breeding, has entered a molecular era thanks to advances in molecular genetics and DNA technologies [36]. Mutations are heritable alterations in an organism's phenotype. Chemical alterations at the gene level are the cause of these modifications. These modifications have the potential to give rise to new and heritable character variants in crop plants. These chemicals can be used to cause mutations in crop plants, and the desired variants that result can be chosen [21]. Mutation breeding [26] is a method of plant breeding in which new varieties of crops with desirable characteristics are generated using induced mutations.

Freisleben and Lein created the term "mutation breeding" to describe the deliberate induction and development of mutant lines for agricultural improvement [21]. Mutagenesis is the process of changing an organism's genetic information in a stable manner. This occurs naturally as a result of mistakes in DNA repair. Mutagenesis is the process of generating mutations [18].

Mutation is a natural process that results in the creation of new gene variants (alleles). Recombination of alleles on homologous chromosomes and their independent assortment at meiosis amplifies the variety acquired in this way [8]. In numerous food crops, mutation breeding and plant mutagenesis play an important role in enhancing genetic variety for desired qualities. One of the most effective tools for identifying critical regulating genes and molecular pathways is induced mutagenesis [9].

We are currently experiencing new impulses in plant mutation research, ranging from fundamental investigations of mutagenesis to reverse genetics, thanks to great advancements in plant molecular biology and biotechnology, notably plant genomics [40]. Breeders are now more aware of the induced mutation technique's fresh potentialities and far-reaching ramifications, and are able to apply it with greater sophistication and efficiency than ever before [46]. The goal of this analysis is to evaluate mutant breeding, its history, application benefits, and drawbacks in plant breeding.

2. Literature Review

2.1. Mutation Breeding

The rapid advancement of plant molecular genetics and genomics in areas important to mutation breeding has re-energized this breeding strategy; mutation breeding is predicted to gain directly from quick scientific and technological developments in molecular genetics and genomics [39]. Plant breeding can only improve when the breeder has access to sufficient variety for a given trait [44].

Plant breeding and mutant breeding are both considered applied genetics [39]. The discovery of experimental mutagenesis in the early twentieth century, which eventually led to plant mutant breeding, was one of the most significant advances in the history of genetics. Plant breeding for crop enhancement necessitates genetic variation in beneficial properties. Mutagenic substances, like as radiation and some chemicals, cause desired alteration [32].

There have been 2252 mutant variants developed in plant species all across the world. 1585 have been released directly, while 667 have been released through the use of mutants in hybridization. 1700 mutant variants have been introduced in seed propagated crops and 552 in vegetatively propagated species, out of a total of 2252. Rice (434 mutant variants) has the most mutant varieties created among seed propagated species, followed by barley (269), and wheat (269). (222). Radiations have resulted in the development of maximum varieties. EMS resulted in the creation of the most mutant variants among chemical mutagens [23].

There are 3222 entries in the Mutant Variety Database, with 2456 seed propagated plants and 367 vegetatively propagated plants. The above classification is based on the entry's common name. Rice, barley, chrysanthemum, wheat, soybean, and maize are the top six crops [17]. Surprisingly, better agronomic and botanic properties characterize the majority (48 percent) of the mutant varieties recorded in the Mutant Variety Database. This could be owing to the fact that botanic and agronomic features are easily observable, and for the most part, screening does not require specialized equipment [49].

2.2. History of Plant Mutagenesis

The history of mutation induction may be traced back to 300 BC in China, when tales of mutant crops were first reported. However, significant modifications have been made to boost the mutation frequency from the beginning to the present [32]. Natural variation (building blocks) for species evolution has been provided by genetic change (mutation). Changes in species have been significant not just for adaptation to the natural environment, but also for agricultural purposes such as species domestication and crop enhancement [5].

The first induced mutant variety was var. Chlorina, a pale green tobacco that was produced in Indonesia in 1936. Several other induced mutant variants were introduced in a variety of plant species during the next few decades, including the tulip var [40]. The first documentation of mutant selection in plant breeding: maturity and other traits in cereals in China is found in an ancient Chinese book. The first verifiable (spontaneous) plant mutant, the larger celandine 'incisa' mutant, was described in 1590 [2].

Table 1. *Summary of plant mutation research and application history.*

Period I: Observation and documentation of early spontaneous mutants	
300 BC	Early mutant crops in China.
1590	The ‘incisa’ mutant of Chelidonium majus.
1672	Variability in plants.
17th century	‘Imperial Rice’ in China: a spontaneous mutant?
Late 17th century	Spontaneous mutant for the ornamental ‘morning glory’ (Ipomoea nil) in Japan.
1741 and following years	Description of various mutants by Carl von Linné.
1859	“The Origin of Species” published by Charles Darwin.
1865	E. A. Carriére publishes his book: ‘Production et fixation des variétes dans les végétaux’.
1894	W. Bateson published: “Materials for the Study of Variation, treated with special regard to Discontinuity in the Origin of Species”.
Period II: Conceptualization of mutation and mutation breeding	
1895-1900	The discovery of various kinds of radiation (X-rays, α, β and γ radiation).
1897-1908	Early work on irradiation of plants: mostly physiological effects and damage to nuclei and cell division.

1901	Hugo de Vries, coined the term 'mutation' for sudden, shock-like changes of existing traits. 'Die Mutationstherorie' of Hugo de Vries published. 'Theory of Heterogenesis' published by S. Korschinsky.
1901 and 1911	First proof of mutations induced by chemicals in bacteria.
1904 and 1905	Hugo de Vries suggests artificial induction of mutations by radiation.
1907	P. J. S. Cramer's work on bud variations
1909 – 1913	W. Johannsen describes spontaneous drastic mutations and slight mutations affecting seed index.
1910	Thomas Hunt Morgan: first mutation experiments with Drosophila melanogaster.
1920	N. I. Vavilov's 'law of homologous series of variation'.
Period III: Proof of induced mutations and release of the first commercial mutant varieties	
1926	N. I. Vavilov's theory on gene diversity centres or 'Centres of Origin'.
1927	C. Stuart Gager & A. F. Blakeslee report on induction of mutations in Datura stramonium. Definite proof of mutation induction by X-rays by H. J. Muller, indicating the possibility of obtaining genetically superior plants, animals and man by applying X-radiation.
1928	Successful induction of mutations after irradiation of barley and maize by Lewis John Stadler.
1928-34	Continued studies on mutation theory and practical applicability.
The 1930s	Start of the Swedish mutation research programme by Åke Gustafsson.
1934/1938	The first commercial mutant variety 'Chlorina' obtained after X-radiation in tobacco by D. Tollenar released in Indonesia.
1934 and following year	The physical mutation theory – Hit and Target Theory was established by N. W. Timoféeff- Ressovsky and co-workers.
1937	The chromosome doubling effect of colchicine on plant chromosome.
1941	Chemical mutagenesis: C. Auerbach, I. A. Rapoport, F. Oehlkers and others.
1942	First report on X-ray induced resistance in barley.
1951	Barbara McClintock reported controlling elements (later established as transposable genetic elements or transposons).
1953	The Watson-Crick model of the gene.
The early 1950s	Mutations induced by gamma rays were produced in Gamma field by chronic irradiation, but the first evidence that gamma rays do induce mutation was not clear.
1956	E. R. Sears transfers resistance from Aegilops to wheat by radiation-induced translocation.
1958 and following year	Application of chemical mutagens on higher plants
Period IV: Large-scale application of mutation breeding	
1964	Establishment of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture at Vienna, Austria; Internationally coordinated mutation breeding research programmes were launched.
1960s	Numerous national research institutes specialized on Nuclear Techniques in Food and Agriculture were established.
1969	The Pullman Symposium on Induced Mutations in Plant Breeding: The first classified list of mutant varieties published.
1981	First major symposium on the 'Use of Induced Mutations as a Tool in Plant Research' organized by FAO/IAEA at Vienna, Austria.
1990	Joint FAO/IAEA symposium in Vienna, Austria to assess results of 25 years of applied mutation breeding.
Period V: Integration of plant mutation with biotechnology and genomics	
1983	Four groups independently reported the production of first transgenic plants, laying down the basis of T-DNA insertion mutagenesis.
1983	The transposable controlling elements Ac and Ds were isolated, laying down the basis of transposon mutagenesis using Ac-Ds and modified genetic systems.
1997	Retrotransposons were re-activated via tissue culture in rice, which prompted the establishment of the large Tos 17 mutant collection. The first plant genome (Arabidopsis genome) was sequenced.
2000	Methodology for targeted screening of induced mutations established, which is now widely known as TILLING (Targeting Induced Local Lesion IN Genomes).
2002-2005	Genomes of the indica and japonica rice subspecies were sequenced.
2005	Establishment of mutant populations for functional genomics studies, including TILLING and T-DNA insertion mutant populations in crop plants
2008	International Symposium on Induced Mutations in Plants in Vienna, Austria to assess applications of induced mutation in plant mutation research and breeding in the genomics era.

*Adapted from A. M. van Harten (1998) for Period I ~ IV with addition/deletion of a few events.

In the 1950s, 1960s, 1970s, and 1980s, mutation induction activities peaked, with considerable accomplishments in terms of mutant variety releases [40]. Mutation technologies experienced a comeback in the early twenty-first century as a result of a faster and better knowledge of mutagenesis and associated disciplines, which led to new applications [28]. Mutation breeding was also able to embrace and utilize the most recent results and technological breakthroughs in plant genomes and molecular biology research thanks to the use of molecular and genomic tools for mutant screening and characterization [20].

Several countries, including China, India, Pakistan, Bangladesh, Vietnam, Thailand, Italy, Sweden, the United States, Canada, and Japan, have used induced mutagenesis and mutation breeding to develop superior mutant varieties in a wide range of important agricultural crop species, including cereals, pulses, oilseeds, vegetables, fruits, fibers, and ornamentals. The mutant varieties created so far have enhanced a wide variety of characteristics, including yield, maturity, quality, and tolerance to biotic and abiotic challenges [34].

2.3. Types of Mutation Breeding and Mutagenesis

Mutagenesis is the process of an organism's genetic information changing owing to mutagen exposure, resulting in mutation. It can happen naturally or be created in a lab. Genetic modification, on the other hand, is the act of altering the genetic makeup of cells in laboratories, which involves the transfer of genes between species and within species to create animals with desired qualities [32]. Mutations can cause structural changes in an encoded protein, as well as a reduction or full loss of its expression. Mutations can be particularly harmful to a cell or organism since a change in the DNA sequence affects all copies of the encoded protein [11].

2.3.1. Spontaneous Mutation

Spontaneous mutations are mutations that occur in natural populations with a relatively low frequency. Spontaneous mutations are ones that develop naturally rather than as a result of human involvement [22]. Because these mutations occur at random, the cause of them is difficult to pinpoint. Even in a healthy, uncontaminated cell, spontaneous mutations have a non-zero chance of occurring. In humans, oxidative DNA damage occurs 10,000 times per cell per day, while in rats, it occurs 100,000 times per cell per day. The specific change can be used to identify spontaneous mutations [33].

Deamination of cytosine to uracil in the DNA double helix is a common source of spontaneous point mutations. Following replication, a T•A base pair replaces the wild-type C•G base pair, resulting in a mutant daughter cell. Copying mistakes during DNA replication are another cause of spontaneous mutations. Despite the fact that replication is normally carried out with high fidelity, errors do occur [31].

2.3.2. Induced Mutation

Mutation can be generated artificially using mutagenic agents [21]. Mutations can be induced using mutagens or mutagenic agents, which are chemical or physical agents that enhance the frequency of mutations. Mutations induced this manner are referred to as induced mutations. Induced mutations occur when a gene comes into contact with mutagens or other environmental factors [41].

Induced mutations are caused by irradiation (gamma rays, X-rays, ion beams, etc.) or chemical mutagens; site-directed mutagenesis is the process of creating a mutation at a specific location in a DNA molecule; and insertion mutagenesis is caused by DNA insertions, either through genetic transformation and insertion of T-DNA or transposable element activation [32]. Researchers frequently use high dosages of chemical mutagens or subject experimental organisms to ionizing radiation to increase the frequency of mutation. Induced mutations are mutations that occur as a result of such interventions. Chemical mutagens, on the other hand, cause point mutations, whereas ionizing radiation causes extensive chromosomal abnormalities [4].

2.3.3. Insertion Mutagenesis

DNA insertions, either by genetic transformation and insertion of T-DNA (T-DNA insertion mutagenesis) or activation of transposon elements, cause this type of mutagenesis (transposon mutagenesis or transposition mutagenesis). Insertion mutants or transposon mutants are the resulting mutants [47].

2.3.4. Site-directed Mutagenesis

The act of producing a mutation at a specific location in a DNA molecule is known as this sort of mutagenesis [6]. This is accomplished in plants by genetic transformation and homologous recombination of the T-DNA fragment with indigenous DNA molecules. The mutants are defined by the substitution of a foreign molecule for an indigenous DNA segment, which can be as little as one nucleotide [25].

2.4. Importance of Mutation in Breeding

Plant breeding, including mutant breeding, has entered a molecular era thanks to advances in molecular genetics and DNA technologies [10]. When compared to traditional approaches, molecular mutation breeding has the potential to improve plant breeding efficiency and power [15]. Plant mutagenesis using physical or chemical agents is a well-known crop enhancement approach.

Rapid advancements in molecular genetics and genomics have made a variety of DNA technologies available for crop improvement, as well as transforming breeding and bringing molecular plant breeding methodologies to fruition [27]. The generation of crop products with novel features is another key function that mutant breeding has played and will continue to play in the future. As previously said, new cereal and legume mutant varieties with low phytate content or high resistant starch content are suitable examples. Many food crop mutation breeding programs are actively pursuing anti-nutrient less/free novel variations, or varieties with high concentration of micronutrients, vitamins, anti-oxidants, and other nutrients [48].

Some fundamental genetic investigations (dominance determination, mapping, allelism testing, etc.) were carried out as mutation research progressed, but it wasn't until molecular biology that the molecular basis of mutant events could be examined and used in gene discovery and breeding (Powell, 1997). Techniques in molecular genetics are quickly improving, and bioinformatics tools for processing enormous data sets are predicted to have a significant impact on molecular mutation breeding [14].

Crop genetic improvement is critical for long-term success, and it necessitates a combination of innovative innovations and translational science [13]. We believe that induced mutagenesis will continue to be a useful technique for breeders because it is a quick and low-cost way to develop new alleles and phenotypes. Furthermore, new technologies will make it possible to identify the mutant alleles that were employed to develop successful mutant varieties, as well as give light on gene function and agricultural productivity [17]. Gene functional research and genetic variability can both benefit from mutations. To determine gene function, forward genetics (from phenotype to gene) or reverse genetics (from gene to phenotype) examination of mutants can be used [42].

The utility of mutant breeding in crop improvement was first established in Sweden, which used X-rays and ultra violet generated mutations to begin practical plant breeding of agricultural plants [38]. They discovered mutants with dense heads, late maturity, and extremely stiff taller straw. These mutants produced more straw and yielded greater yields than the mother variety. The green revolution's production of dwarf wheat and rice varieties is a typical example of mutation breeding accomplished by successful exploitation of mutant genes [24].

2.5. Advantages and Disadvantages of Mutation

Table 2. *Generally the importance and impact of mutation are summarized below.*

Advantages	Disadvantages
Direct mutants varieties are possible, or limited breeding effort required.	A heavy mutational load (mutation density) may require intensive breeding to reduce background mutations and eliminate chimeras.
For some mutagenic treatments such as gamma and X-ray, there is neither residual radiation nor chemical contamination of the treated material. The treated material is safe to handle.	Field trialing and germplasm storage can be expensive and require a lot of space and careful management if large mutant populations are handled. However, effective screening and selection for desired mutants at an early stage can negate this problem
Induced mutagenes is used for the induction of CMS.	Health risks: careful handling and disposal of waste chemical mutagens; background radiation in fast neutron treatments needs to decay before handling treated material.
Mutation breeding is a cheap and rapid method of developing new varieties.	Large population sizes and effective mass screening methods are required to select rare mutants.
Mutation breeding is more effective for the improvement of oligogenic characters.	Most mutants are of no use to breeding even if a large number of mutants can be produced.
Mutation breeding is the simple, quick and the best way when a new character is to be induced	Mutants can have strong negative pleiotropic effects on other traits, e.g. high lysine/protein in barley and low lignin/high digestibility in maize are associated with low yields (pleiotropic effects however are an issue in all forms of breeding).
Novel variation can be produced.	The number of lines/families in a generation can mushroom after the M1 generation.
Possible to achieve instant progress in elite material.	The process is generally random and unpredictable.
Possible to calculate chances of success (mutation frequency).	Unknown interactions with environmental factors, performance may vary significantly in different environments (this is an issue in all forms of breeding).
Production of environmental responsive traits (e.g. flowering, fertility under various day lengths).	Useful mutants are rare and predominantly recessive.
Single gene mutants with no negative pleiotropic effects are possible.	
Single trait improvements can be made to an established variety preferred by producers, processors and/or consumers.	
Specific genes/traits can be targeted.	

2.6. Achievements of Mutation Breeding

Higher yield, earliness, stress resilience, salt tolerance, water logging tolerance, and bold seed size are some of the benefits of mutant breeding [3]. In wheat, rice, and barley, improved varieties have been generated by mutation breeding. In addition to high yield, improved quality, earliness, dwarfness, disease resistance, and reduced toxin content have all been created in numerous crop varieties. Mutation has also been employed to induce male sterility, which lowers the cost of hybrid seed production, increases the range of genetic variety, and aids crop adaptation.

There have been 2252 mutant variants developed in plant species all across the world. 1585 have been released directly, while 667 have been released through the use of mutants in hybridization. 1700 mutant variants have been introduced in seed propagated crops and 552 in vegetatively propagated species, out of a total of 2252. Rice (434 mutant variants) has the most mutant varieties created among seed propagated species, followed by barley (269), and wheat (222). Radiations have resulted in the development of maximum varieties. EMS resulted in the production of maximal mutant variations among chemical mutagens [1].

3. Conclusion

Mutation breeding is a modern approach of plant breeding that is used to improve crop adaptability, establish improved varieties, induce male sterility, produce haploids, and promote genetic variability. Induced mutagenesis is one of the most effective strategies for creating genetic variation and identifying critical regulatory genes for economically relevant features in crop development. Recent developments in genomics technology have resulted in a proliferation of genomic techniques in applied breeding, notably mutational breeding. Plant breeding has employed mutagenesis, or the act of creating mutations within an organism's genome. Induced mutagenesis and associated breeding tactics have the ability to improve quantitative and qualitative qualities in crops in a fraction of the time it takes to do so with traditional breeding. The global effect of mutation breeding-derived agricultural types highlights mutation breeding's promise as a versatile and practical approach to any crop.

Conflict of Interest

The authors declare that there are no competing interests in the paper's publication.

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