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10. Polyploidy: Feature and Applications

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Abstract

Polyploidy, a condition in which an organism complements more than two sets of chromosomes, has long been recognized as a key factor in plant evolution and speciation. Polyploidisation has greatly assisted plant breeders to create novel varieties with a wide range of desirable traits, contributing significantly to the advancement of agriculture and food production. Polyploids are mainly classified into auto, allo and segmental allopolyploids which are further divided into many others. It also aids in the creation of new species and thus plays a major role in evolution. There are several evolutionary consequences, constraints and potential of polyploids that are yet to be realized. This chapter provides the insights into polyploidy, its features and wide applications.

Keywords:

Polyploidy, Evolution, Autopolyploidy, Allopolyploidy, Segmental allopolyploidy

10.1 Introduction:

Ploidy refers to the variation in the number of copies of entire chromosome set (x) or variation in chromosome number in the body cells of an individual. Polyploidy or genome doubling, a fascinating genetic phenomenon, occurs when organisms have more than two complete sets of chromosomes. It can happen naturally or be triggered artificially in plants and animals. The word itself comes from "poly," indicating many, and "ploidy," which denotes the number of sets of chromosomes in a cell. Polyploidy has been and continues to be a pervasive force in plant evolution (Adams & Wendel, 2005). Polyploidy has been observed in both somatic and germ cells, and in both prokaryotic and eukaryotic organisms. Nevertheless, polyploidy is well tolerated in many groups of eukaryotes. Indeed, the majority of flowering plants and vertebrates have descended from polyploid ancestors. (Otto, 2007). Consequently, although often considered an evolutionary dead end, the short-term adaptive potential of polyploidization is increasingly being acknowledged.(Van de Peer *et al.*, 2017). Moreover, once established, the distinct retention pattern of duplicated genes after whole-genome duplication could elucidate significant long-term evolutionary shifts and a broad enhancement in biological intricacy.

It occurs frequently in both plants and mammals. It is one evolutionary mechanism which aids in speciation, diversification, and adaptation to changing environmental conditions (Yali, 2022). Genome sequencing and related molecular systematics and bioinformatics studies on plants and animals in recent years support the view that species have been shaped by whole genome duplication during evolution.

Polyploidy is widespread among plants, with a significant presence in various groups. Bryophytes, for instance, show polyploidy in approximately 53% of their species, while pteridophytes exhibit rates as high as 95%.

Gymnosperms follow with about 38% being polyploids (Song *et al.*, 2012), and the prevalence is even more pronounced in angiosperms, where around 70% of species are polyploid including autopolyploid species like *Medicago sativa* (alfalfa) and potato, as well as allopolyploid species such as wheat, cotton, rapeseed, oats, and coffee (Li *et al.*, 2024). Polyploidy is a key mechanism of genome evolution and speciation, particularly in plants (Doyle & Coate 2019). Polyploidy is currently an interesting research topic for understanding agricultural plant evolution and utilizing its diversity in crop breeding.

10.2 Classification of Ploidy:

Polyploidy, or having more than two genomes per cell, is a common way of plant species creation (Vimala *et al.,* 2021). In literature on polyploidy, the fundamental chromosome number is typically denoted as x, representing the complete set of chromosomes or a genome. The chromosome count in the gametophyte phase, and consequently in gametes, is termed the gametic chromosome number, often represented as n.

While in diploid organisms x equals n, in higher levels of polyploidy, this equivalence no longer holds true. There are two main categories of ploidy in plants. The first, euploids, encompasses plants with one or more complete sets of chromosomes in their genome. The second, aneuploids, consists of plants with partial sets of chromosomes, either due to the absence of at least one chromosome or the presence of at least one additional chromosome.

10.2.1 Euploidy:

Euploids are polyploids with multiples of the complete set of chromosomes specific to a species. Depending on the composition of the genome, euploids can be further classified into either autopolyploids or allopolyploids.

A. Monoploidy and Haploidy:

Presence of single copy of single genome constitutes monoploidy. In polyploidy literature it is denoted by x. Monoploids are nothing but the haploids of diploid species. Haploidy in the case is the gametic chromosome number of any species irrespective of their ploidy level and it is denoted by n. For instance, consider potato having autotetraploid genome *ie.*, $2n=4x=48$ having four basic chromosome sets. Its haploid state contains two basic chromosome sets *ie.,* $n=2x=24$. Therefore, it can be said that all monoploids are haploids but all haploids need not to be monoploids.

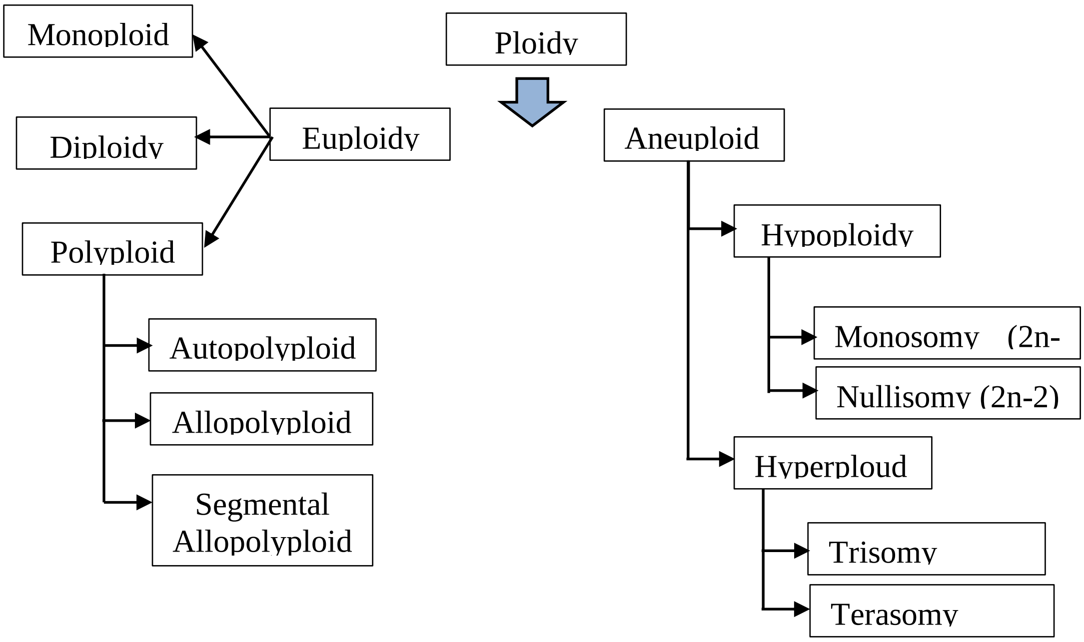


Figure 10.1: Classification of ploidy

B. Polyploidy:

Polyploidy, characterized by the presence of three or more sets of chromosomes resulting from whole-genome duplication (WGD), exerts a profound influence on organisms across all clades of eukaryotic life and at every level of biological organization. This influence spans from the molecular level of genes to the cellular level and extends to entire ecosystems. Polyploidy is further classified in to autotpolyploidy ,allopolyploidy and segmental alloploidy.

a. Autoployploidy:

Polyploids which originate by multiplication of the chromosome of a single species are known as autopolyploids or autoploids and such situation is termed as autoployploidy. It may also referred as situation in which additional set of chromosomes arise from the same species.

Autopolyploids may have three (triploid), four (tetraploid), five (pentaploid), six (hexaploid), seven (heptaploid), eight (octaploid) or more copies of the same genome. In nature, autoploids arise when unreduced gametes unite, and they can also be deliberately created through artificial means (Chen, 2010).

Natural autoploids include tetraploid crops such as alfafa, peanut, potato and coffee and triploid bananas (Table 10.1). They occur spontaneously through the process of chromosome doubling

Table 10.1: List of Major Crops and Their Ploidy

Common name	Ploidy	Common name	Ploidy
Maize	2x (diploid)	Sugarcane	8x (octaploid)
Wheat	6x (hexaploid)	Sugarbeet	2x (diploid)
Sweet potato	6x (hexaploid)	Cassava	2x (diploid)
Potato	4x (tetraploid)	Coffee	4x (tetraploid)
Barley	2x (diploid)	Lucerne	4x (tetraploid)
Tomato	2x (diploid)	Peanut	4x (tetraploid)
Banana	3x (triploid)	Rice	2x (diploid)

b. Allopolyploidy:

Allopolyploids contain two or more distinct genomes, which are derived from different species. They are also referred as organisms which originates by combining complete chromosome sets from two or more species is known as allopolyploid or alloploid or hybrid polyploids or bispecies and such situation is known as allopolyploidy. An allopolyploid may be a allotetraploid also termed as amphidiploid which arises by combining genomes of two diploid species, in the same way allohexaploid arises from combining genomes of three diploid species. Most naturally occurring polyploids are allopolyploids. Allopolyploidy may occur naturally or can be induced artificially. Some commonly known allopolyploid species includes wheat, cotton, tobacco, Brassica species, oats etc.

c. Segmental Alloploidy:

Segmental aneuploidies (SAs) are structural imbalances, namely, gains or losses, involving a chromosomal segment. In these, the distinct genomes they contain may exhibit some similarity. As a result, chromosomes from different genomes have a degree of pairing, forming multivalents. This indicates that only segments of chromosomes, rather than entire chromosomes, are considered homologous and such polyploids are known as segmental allopolyploids(Stebbins, 1947).

10.3 Mechanisms of Polyploidy Formation:

In common, mechanism of polyploids formation involves three different ways viz., chromosome doubling, meiotic nuclear restitution or non reduction and polyspermy.

Several cytological mechanisms are known to induce polyploidy in plants. Naturally occurring allopolyploids are believed to have originated primarily through the process of chromosome doubling in F1 hybrids. These hybrids are formed by chance through natural hybridization between two distinct species, facilitated by irregular mitosis.

This irregular mitosis can lead to the creation of doubled sectors in the apical meristem or axillary buds of plants. The descendants of such branches, known as amphidiploids, inherit the complete chromosome sets from both parental species.

One of the major route leading formation of polyploid species is non reduction or meiotic nuclear restitution during formation of male and female sporogenesis. This non reduction process will produce unreduced gametes *ie.,* 2n gametes containing its complete somatic chromosome number. Fusion of this formed 2n gametes with reduced gametes or fusion between two unreduced gametes leads to formation of polyploid species.

Another pathway is through polyspermy where female gamete *ie.,* egg is fertilised by several male nucleus which is commonly observed in ornamental plants like orchids.

10.3.1 Phenotypic Effects of Polyploidy:

The impact of polyploidization on evolutionary innovation largely hinges on its influence on the phenotype. Consequently, the pivotal inquiry is whether polyploidization inherently drives phenotypic changes that hold adaptive value. Chromosomal duplications and increases in DNA amount have the potential to alter quantitative plant traits like flower number, plant stature or stomata size. This has been documented often across species, but information on whether such effects also occur within species (*i.e.,* at the microevolutionary or population scale) is scarce (Balao *et al.,* 2011). Polyploidy, whether autopolyploidy or allopolyploidy, can lead to notable changes in the observable traits of organisms. These changes typically arise due to the higher genetic redundancy and altered gene dosage resulting from the existence of multiple chromosome copies. Several typical phenotypic effects of polyploidy include:

A. Effect on Cell Size and Growth Rate:

Among the most common and universal effects of polyploidization is increased cell volume although the extent to which this occurs varies and may depend on environmental conditions (Otto & Whitton, 2000). The increase in nuclear ploidy affects the structural and anatomical characteristics of the plant. In general, polyploidy results in increased leaf and flower size, stomatal density, cell size and chloroplast count (Meru, 2012). These phenomena are collectively referred to as the gigas effect (Acquaah, 2007). Its application in forage and ornamental breeding is described later in this chapter.

In Arabidopsis, examining leaf morphology revealed that polyploidy influenced the characteristics of epidermal pavement cells, resulting in larger cell size and fewer cells per leaf blade as ploidy increased. Interestingly, tetraploids exhibited the highest dry weight in the inflorescence stem (Corneillie *et al.,* 2019). Tetraploid plants exhibited an array of characteristics compared to their diploid counterparts: larger leaves, taller and thicker stems, denser branching, longer trichomes, larger stomata, larger guard cells, and a reduced number of stomata.

Additionally, tetraploid plants showed a significant increase in the number of chloroplasts and mitochondria, by 1.66 and 1.63 times, respectively (Mohammadi *et al.,* 2023). growth and developmental rates of polyploids are generally less compared to diploids. These alterations in developmental rates could impact the probability of seedling establishment in environments with limited resources. Consequently, they may lead to niche differentiation as an unintended outcome of polyploidization.

B. Effect on Size and Shape:

Accompanying genome doubling and increases in genetic materials, the cell volumes of polyploids usually enlarge. Plants and animals may employ different strategies to cope with the increase in cell size associated with polyploidy (Mable, 2004). Polyploid plants maintain the same number of cells as diploids and thus develop larger organs and body sizes. Leaf size is influenced by both the number and size of cells. However, leaves are not merely the outcome of adding up cell size and number. Instead, their development is governed by an unidentified, comprehensive system of integration across the entire organ. This inference is supported by two puzzling phenomena: compensation and high-ploidy syndrome (Tsukaya, 2008).

C. Effects on Reproductive Systems:

One of the frequent changes observed in the reproductive system associated with polyploidy is the shift towards asexual reproduction. While many plants that reproduce via apomixis are polyploid, the majority of polyploid plants do not exhibit apomixis. Conversely, in animals, about two thirds of polyploids reproduce through parthenogenesis. Apart from transitions to asexual reproduction, plants also experience various alterations in their breeding systems due to high ploidy levels. One notable effect is the gigas effect, wherein increased ploidy disrupts the natural floral architecture. This disruption can impede the effective pollination by traditional pollinating agents. Over evolutionary time, this may prompt a shift in reproductive methods as plants adapt to these changes.

10.3.2 Genetic Effects of Polyploidy:

A. Genomic Change after Polyploid Formation:

Genomic rearrangements occur throughout the lifespan of an established polyploid, which may promote its long-term diversification and existence. As per the genomic shock hypothesis, disruptions within the genome, like polyploidization, could result in extensive alterations in epigenetic control. One more change in gemome seen due to polyploidization is reduction in genome size. An examination of more than 10,000 plant genome sizes (GSs) reveals that many species possess genomes smaller than anticipated based on the occurrence of polyploidy in their evolutionary lineages. This suggests a preference for genome reduction through selection. Nonetheless, when comparing the ancestral genome size with the frequency of ancestral polyploidy, it appears that the pace of DNA reduction subsequent to polyploidy events was probably quite gradual, estimated at 4–70 Mb per million years or 4–482 bp per generation (Wang *et al.*, 2021). By using AFLP markers in autopolyploid *Phlox drummondii*, loss of DNA sequences was also observed after few generations of autopolyploidization (Dar *et al.*, 2013).

B. Changes in Gene Expression in Polyploids:

While it might seem logical that an increase in the copy number of all chromosomes would lead to a uniform increase in gene expression, the reality is more complex.

Polyploidy can indeed lead to changes in gene expression, but these changes may not always be uniform across all genes. In diploid organisms, gene expression is typically regulated by complex networks of transcription factors and other regulatory molecules. These networks form hierarchical structures that control the expression of genes across various cellular processes.

However, in polyploid organisms, the number of regulators within these networks can increase significantly. For instance, while diploid networks already contain a high number of regulators, the number can expand several times over in polyploid organisms. This expansion of regulatory elements in polyploids can significantly alter the dynamics of gene expression and cellular function (Osborn et al., 2003).

10.4 Role in Evolution:

Autopolyploids found in nature encompass tetraploid crops like alfalfa, peanut, potato, and coffee, as well as triploid bananas. These arise naturally through the spontaneous doubling of chromosomes.

The impact of chromosome doubling in autopolyploids varies depending on the species. Notably, spontaneous chromosome doubling in ornamental plants and forage grasses has resulted in heightened vigour. Recognizing the benefits observed in natural settings, breeders have actively utilized induced polyploidy, replicating chromosome doubling in vitro, to develop enhanced crop varieties. For example, induced autotetraploids in the watermelon crop are used for the production of seedless triploid hybrids fruits. Autopolyploid contribute a limited role in evolution.

Allopolyploidy is key in the process of speciation for angiosperms and ferns (Chen, 2010) and occurs often in nature. Economically important natural alloploid crops include strawberry, wheat, oat, upland cotton, oilseed rape, blueberry and mustard (Chen, 2010). Allopolyploids have been more successful as crop species than autopolyploids.

Since most of our daily day crops are allopolyploids their contribution to evolution is highly considerable. Naturally occurring allopolyploids are believed to have originated primarily through the process of chromosome doubling in F1 hybrids. To distinguish between the origins of the genomes in an allopolyploid, each genome is assigned a unique letter designation. A brief description of evolution of wheat and tobacco are given below.

A. Evolution of Wheat:

Triticum aestivum commonly known as common or bread wheat which is an allohexaploid having two copies of each genome A, B and D. The ancestral origins of bread wheat (*Triticum aestivum*; AABBDD) have been a focal point of contention and scholarly discussion in the scientific realm for several decades. In 2015, three articles published in New Phytologist delved into the debate surrounding the emergence of hexaploid bread wheat (AABBDD) from its diploid progenitors: *Triticum urartu* (AA), a close relative of *Aegilops speltoides* (BB), and *Triticum tauschii* (DD) (Baidouri *et al.,* 2017).

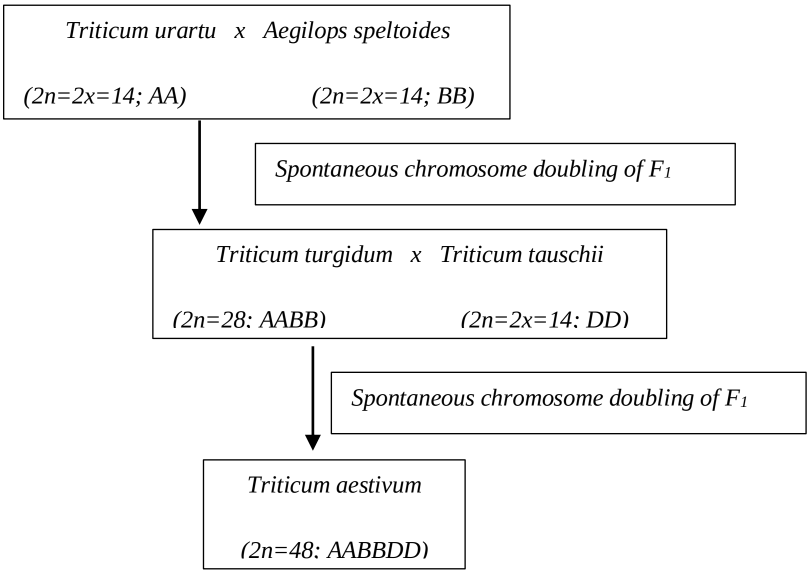


Figure 10.2: Evolution of common wheat *Triticum aestivum*

B. Evolution of Tobacco:

In the same way tobacco *(Nicotiana tabacum)* is also a allotetraploid having 24 chromosomes in each haploid component. Available literature indicates that *Nicotiana tabacum* was derived from inter specific hybridization followed by chromosomal doubling between *Nicotiana sylvestris* and *Nicotiana tomentosa.*

10.5 Advantages and Disadvantages of Polyploidy:

Due to the high incidence of polyploidy in some taxa, such as plants, fish, and frogs, there clearly must be some advantages to being polyploid. A common example in plants is the observation of hybrid vigour, or heterosis, whereby the polyploid offspring of two diploid progenitors is more vigorous and healthier than either of the two diploid parents.

In the short term, polyploidy may lead to transgressive segregation and increased vigour. In the context of adaptation, the adaptive scenario posits that polyploids possess the capacity to swiftly adjust to harsher environments due to heterotic effects and rapid genomic as well as epigenetic alterations.

In both allopolyploids and autopolyploids, heightened heterozygosity can induce greater diversity in gene expression and regulatory networks, potentially enhancing vigor and facilitating quicker adaptation to new environmental conditions (Van De Peer *et al.*, 2009) . enhanced adaptability is also an advantage provided by polyploidy where increased resistance to a variety of environmental stresses, including disease, salt, and drought, is frequently seen in polyploid plants.

The redundancy of genetic material, which acts as a buffer against harmful mutations and permits the development of advantageous features, is responsible for this increased flexibility. Genome duplications frequently coincide with significant and abrupt rises in species richness.

While the connection between a particular genome duplication event and heightened species diversity remains correlational rather than causative, several mechanisms could elucidate how gene duplication fosters the emergence of new species. Over time, polyploidy has the potential to facilitate evolutionary innovations or enhancements of existing morphological features, enabling the exploration of fundamentally distinct regions within the phenotype space. Another benefit provided by gene redundancy is the capacity to diversify gene function gradually.

In essence, surplus gene copies that aren't essential for regular organism functioning could eventually find utility in novel and completely distinct roles, thus presenting new avenues for evolutionary selection (Adams & Wendel, 2005). Polyploidy can affect sexuality by disrupting certain self-incompatibility systems, allowing self-fertilization. In allopolyploids of A. thaliana, this phenomenon could arise due to interactions between the parental genomes.

In the autopolyploid Petunia hybrids, it might stem from interactions among alleles in the 2X pollen (Comai, 2005). Another advantage conferred by polyploidy is gene redundancy which is the masking of recessive alleles by dominant wild-type alleles. Polyploidy leads to instantaneous reproductive isolation of polyploid individuals. Multiple observations suggest a positive association between species richness and percent polyploid species in different plant clades (Moghe & Shiu, 2014).

Along with advantages several disadvantages of polyploidy both theoretical and documented were present. One of them is difficulty in breeding because polyploidy relates to complicated genetic interactions and cytological obstacles, breeding crops with polyploidy can be difficult. In polyploid crops, cytogenetic manipulation, selection, and extensive backcrossing may be necessary to achieve stable and desired characteristics. One drawback concerns the proportional changes between genome size and cell volume. Cell volume is directly linked to the amount of DNA in the nucleus.

For instance, doubling a cell's genome would theoretically double the volume occupied by chromosomes in the nucleus, but it would only result in a 1.6-fold increase in the surface area of the nuclear envelope (Melaragno et al., 1993). This disproportion can upset the equilibrium of factors that typically govern interactions between chromosomes and nuclear components, including proteins bound to the envelope (Comai,2005).

Polyploids can encounter challenges during both mitosis and meiosis. Irregularities may arise during the formation of spindle fibers, potentially resulting in the production of aneuploids.

Epigenetic instability can pose yet another challenge for polyploids. Epigenetics refers to changes in phenotype and gene expression that are not caused by changes in DNA sequence.

According to the genomic shock hypothesis, disturbances in the genome, such as polyploidization, may lead to widespread changes in epigenetic regulation. Transgene silencing occurred more frequently in *Arabidopsis thaliana* tetraploids than in *A. thaliana* diploids, suggesting an effect of ploidy on chromosome remodeling (Mittelsten Scheid *et al.*, 1996).

10.6 Applications of Polyploidy:

A. Creation of New Species:

Triticale, also known as ‘man-made cereal’, is developed from intergeneric hybridization between wheat and rye, which is commercially cultivated in Poland, France, Germany and Canada. The desirable features of triticale such as, yielding ability and quality grain traits were transferred from wheat whereas abiotic stress tolerance like hardness is transferred from rye

Triticum turgidum X *Secale cereale*

(2n= 4x= 28, AABB) ↓ (2n= 2x= 14, RR)

F_1 (sterile)

(2n = 3x = 21, ABR)

↓ Colchicine

AABBRR (2n = 6x = 42)

Triticale allohexaploid

B. Mutation Breeding:

Polyploids play a crucial role in mutation breeding due to their ability to harbour increased genetic variation and to facilitate the fixation of beneficial mutations. With multiple sets of chromosomes, polyploid organisms offer a broader genetic canvas for mutations to occur increasing the likelihood of discovering novel traits that can be exploited for crop improvement. This enhanced genetic diversity provides mutation breeders with a rich pool of potential genetic variations to select from, enabling the development of improved crop varieties with desirable traits such as higher yields, disease resistance or enhanced nutritional content.

Furthermore, polyploidy can mask deleterious mutations, allowing breeders to focus on selecting for advantageous traits without being hindered by the negative effects of recessive mutations.

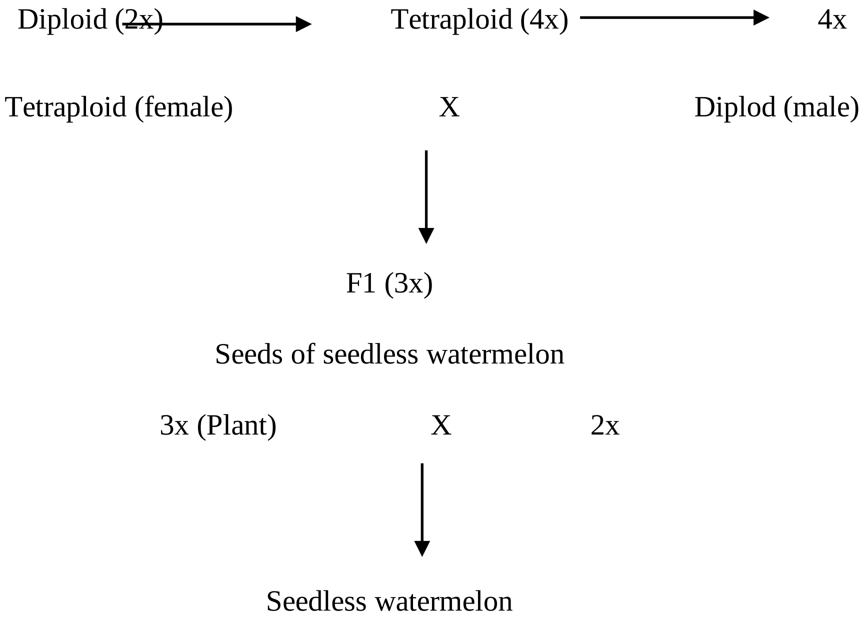
The redundancy of gene copies in polyploid genomes provides a buffering mechanism against the expression of harmful mutations, there by streamlining the process of identifying and harnessing beneficial mutations for crop improvement. This feature enhances the efficiency of mutation breeding programs by reducing the likelihood of encountering undesirable genetic outcomes and increasing the success rate of selecting for desirable traits.

The combination of increased genetic variation, masking of deleterious mutations and enhanced hybrid vigour, polyploids are a powerful toolkit for creating new and improved crop varieties that meet the evolving needs of agriculture and food security.

C. Seedless Fruits:

Polyploidy plays a crucial role in the development of seedless fruits, offering significant advantages in both agricultural production and consumer preference. One notable example is seedless watermelon (*Citrullus lanatus*), where polyploidy has been instrumental in creating popular seedless varieties.

In seedless watermelon production, triploid (3n) plants are commonly used. These triploids are artificially produced by crossing a diploid (2n) male plant with a tetraploid (4n) female plant, resulting in offspring with three sets of chromosomes. This triploid condition often leads to sterility or reduced fertility, preventing the formation of viable seeds in the fruit. China is now the biggest producer of seedless watermelon.



D. Bridge crossing:

Reproductive superiority of polyploids is utilized in bridge crossing, also known as distant hybridization.

One of the key advantages that it offers is greater diversity in their genetic makeup. Polyploids have the ability to overcome the reproductive barriers between distantly related species. Barriers *viz*., differences in chromosome number, structure or genetic incompatibilities, can hinder successful hybridization. However, traditional crosses can be carried out followed by chromosome doubling to produce fertile bridge hybrids. Mostly, amphidiploids serve as bridging species in the transfer of characters from one species to another species.

The F_1 obtained from the cross *Nicotiana tabacum* and *Nicotiana sylvestris* is sterile. Chromosome doubling of this hybrid resulted in a synthetic hexaploid called *N. digluta* which is relatively fertile and is backcrossed to the *N.tabacum* to produce a fertile pentaploid which is further backcrossed to *N.tabacum* where plants resistant to TMV are selected. The same principle has been applied in fixing heterozygosity in hybrids by doubling the chromosomes in the superior progeny (Comai, 2005).

E. Ornamental and Forage Breeding:

Increase in cell size which in turn leads to enlarged plant organs, is one of the clear and immediate effects of polyploidy in plants. This phenomenon is known as gigas effect (Acquaah, 2007). For example, induced polyploidy have enabled breeders to develop Bouschet tetraploid grapes, which have higher yield and juice content as compared to their diploid progenitor Alicante (Olmo, 1952). Polyploidy, also leads to notable changes in plant traits, including leaf and stem thickness, deeper green colouration and altered leaf proportions. These modifications often result in a more robust growth habit and visually appealing foliage. Moreover, polyploid plants tend to exhibit compact growth patterns which can be advantageous in ornamental breeding, as it can lead to manageable plant forms. Polyploid plants typically produce larger, more textured flowers compared to their diploid counterparts as reported by Yamaguchi (1989) in carnation, Takamura and Miyajima (1996) in cyclamen and by Van Tuyal *et al.* (1992) and Griesbach (2000) in lily where tetraploids were reported to produce larger flower and sturdy stem. Additionally, slower growth rate of polyploids allows them to exhibit prolonged or delayed flowering periods, extending the duration of floral display and increasing ornamental value (Levin, 1983).

F. Production of Apomictic Crops:

Application of polyploids in the production of apomictics is significant. Through chromosome doubling polyploidy can disrupt normal meiosis and sexual reproduction pathways leading to the development of apomictic traits which can serve as a valuable genetic resource for breeding programmes.

They can provide a means to preserve and exploit genetic diversity within a species while ensuring the retention of desired traits through apomictic reproduction. They can also offer practical advantages in seed production. Since apomictic seeds are genetically identical to the parent plant, they ensure uniformity and consistency in crop performance, simplifying seed production and maintaining varietal purity. Most apomictic plants are polyploid but most polyploid plants are not apomictic (Otto and Whitton, 2000)

G. Enhancing Stress Tolerance:

Expression of secondary metabolites and defence chemicals can be enhanced when chromosomal number and relevant gene dosage are increased. In allopolyploids the secondary metabolites produced are additive of both the parents which offer polyploids more tolerance to drought, cold, mutagens, herbicides and poor soils. Transfer of leaf rust resistance from Aegilops umbellulate to Triticum aestivum through backcrossing.

In addition, other breeding strategies utilizing aneuploidy have been explored including chromosome deletion, chromosome substitution and supernumerary chromosomes (Acquaah, 2007)

H. Industrial Applications of Polyploidy:

Increase in the ploidy is associated with increase in the copy number of genes which in turn determines the composition and proportion of different metabolites which regulate the production of different bioactive compounds, used commercially in various industries. Aneuploidy has been widely exploited in the breeding of narcotic plants such as *Cannabis, Datura* and *Atropa* as reported by (De Jesus-Gonzalez and Weathers, 2003; Dhawan and Lavania, 1996; Levin, 1983).

Higher quality raw materials, including α-acids was produced by triploids in comparison to diploids of *Humulus lupulus* (Trojak *et al*. 2020). Polyplodisation can also be used to produce plants with higher contents of alkaloids for commercial use as reported by (Xing *et al*.,2011) in *Catharanthus roseus* where increase in ploidy increased the production of vinblastine and vincristine that show strongest anti-cancer activity and increase in the production of pyrethrin, a botanical insecticide of *Chrysanthemum cinerariifolium* by Liu and Gao, 2007.

Production of the antimalarial sesquiterpene artemisinin has been enhanced six fold by inducing tetraploids of the wild diploid *Artemisia annua* L. (De Jesus-Gonzalez and Weathers, 2003). Other plants which showed increased production of terpenes following artificial chromosome doubling include *Carum cari, Ocimum kilmandscharicum* and *Mentha arvensis* (Bose and Choudhury, 1962; Levin, 1983).

I. In Crop Improvement:

Polyploidy has been extensively used in agriculture to develop improved crop varieties. Polyploidy has been extensively used in agriculture to develop improved crop varieties. Polyploids have a competitive advantage over their diploid progenitors due to transgressive segregation, or the production of extreme phenotypes, as well as greater vigor.

Polyploids, particularly allopolyploids, have numerous evident advantages such as larger nutritive organs, faster metabolism, more secondary metabolites, and enhanced stress resistance, according to studies on the growth and biochemical characteristics of natural polyploid plants(Van De Peer et al., 2009).

10.7 Conclusion:

Studies have provided deep insights in to genomic and genetic consequences following polyploidisation events and on how it influences traits such as adaptation, speciation and even the emergence of novel phenotypes. Also, polyploidy in the plants open avenues for the development of early maturing varieties, seedless fruits, sterile lines, high yielding crops and enhanced resistance to stress conditions which makes it important to human kind. By unveiling the mysteries of polyploidy, scientists have gained valuable insights that can be utilized across various fields ranging from agriculture to medicine. Many long-standing questions in polyploidy such as lineage diversification and evolutionary consequences remained unanswered due to insufficient knowledge on many aspects of polyploidy. Therefore, in-depth studies are required to understand the details of mechanisms of polyploidy which are of great significance in breeding and biological evolution.

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