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Polyploidy's role in crop improvement: Overview of its types and uses in plant breeding

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ABSTRACT

Polyploidy is a complex biological mechanism wherein an organism possesses multiple sets of chromosomes. This phenomenon has proved highly beneficial in agriculture, developing high-yielding and resilient crops that withstand various environmental stresses and pests. Furthermore, the breeding process involving polyploids has resulted in substantial growth in agricultural productivity due to their ability to produce crops with desirable genetic traits. Two main types of polyploidies have been employed in improving crop quality - autopolyploids, which arise from duplicating a single genome within a single species, and allopolyploids, which originate from crossing two or more related but distinct species. Each type possesses unique strengths and weaknesses that contribute differently to improving crop production yields.This article aims to provide an all-inclusive overview of the different types of polyploid plants used for plant breeding and how they enhance agricultural productivity. Our discussion will delve into how these plants increase harvests, improve crop quality, combat diseases, resist pests, and enhance drought tolerance while employing plant breeding techniques that involve polyploid organisms. With this understanding, we can understand how using polyploid plants improves food production systems worldwide through increased efficiency and sustainability.

Key words: *Polyploidy, Chromosome doubling, Autopolyploidy, Allopolyploidy, Crop improvement.*

Introduction

Polyploidy refers to a genetic occurrence where an organism's entire genome undergoes multiplication, leading to the formation of cells and individuals with more than two sets of chromosomes (Corneillie *et al*., 2018 and Wang *et al.*, 2021). It plays a significant role in increasing genetic diversity and promoting adaptation. This phenomenon can occur naturally or artificially induced, and it has been observed in various species ranging from plants to animals (Madani *et al*., 2021). The ability of polyploid organisms to possess multiple copies of their genomes provides them with a broader range of genetic material they can rely on for survival (Madlung, 2013). This additional gene dosage allows for increased phenotypic variability that often results in improved fitness and adaptability when faced with environmental stressors such as drought, extreme temperatures, or changes in soil quality (Tossi *et al*., 2022; Seleiman *et al.*, 2021). Consequently, understanding the mechanisms driving polyploid formation and its effects on species evolution has become a critical research area in evolutionary biology and genetics

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(Madlung, 2013). By studying these phenomena closely, scientists can better understand how new species arise and potentially develop new strategies to protect biodiversity (Ramsey and Ramsey, 2014; Van de Peer *et al*., 2020).

Polyploidy has been implemented in plant breeding for more than a century with remarkable results (Trojak *et al.,* 2021). The process has been critical in developing numerous vital crops such as wheat, cotton, and canola (Oliver, 2014). Polyploid plants have more giant cells and organs, resulting in greater yield and quality. They also have more genetic diversity, which helps crops adapt to different environments and pests. (Zhang *et al.,* 2019; Fox *et al.,* 2020). Polyploidy has drawbacks such as sterility, meiotic irregularities, and genomic instability which can hinder its usefulness despite its benefits (Baduel *et al.,* 2018). Polyploidy has benefitted crops beyond wheat, cotton, and canola. Bananas have changed significantly due to selective breeding, as they are a polyploid crop. Red Delicious apples are also tetraploid from crossbreeding two apple varieties. Additionally, strawberries (octoploid) and grapes (hexaploid) are commercially critical polyploid crops used globally for their economic potential (Rousseau *et al., 2009*).

Exploring Polyploidy in Plants: Mechanisms and Types of Formation

Polyploidy, which arises from the complete nondisjunction of chromosomes during either mitosis or meiosis, is a widely recognised event in the botanical realm (Madani *et al.,* 2021). It is so prevalent that it has been identified as one of the primary mechanisms leading to speciation within angiosperms. Polyploidy comes in two forms: autopolyploidy and allopolyploidy (De Storme and Mason, 2014). Autopolyploidy occurs when an individual has multiple sets of chromosomes from the same species due to chromosome duplication during cell division. This results in progeny with more than two sets of chromosomes, all from one species. Allopolyploidy happens when two different species mate and produce offspring with multiple sets of chromosomes from distinct species. Sterility may occur if the offspring have an odd number of chromosomes, but fertility can be achieved if a chromosome duplication error happens during cell division.

Colchicine can artificially induce plant polyploidy (Eng and Ho, 2019). This process triggers polyploidy, creating new plant varieties with desirable traits (Sattler *et al.,* 2016). Inducing polyploidy has numerous benefits, including developing breeds with larger fruit and increased disease resistance. These new plant varieties could significantly impact agriculture by improving crop yields, reducing losses due to disease, and contributing to food security worldwide (Bailey-Serres *et al*., 2019). Although polyploidy can occur naturally under certain environmental conditions, human intervention has allowed us to take advantage of this biological mechanism and create improved plant varieties (Van de Peer *et al.,* 2020). Additionally, polyploidy can result in hybrid vigour or heterosis in plants, making it advantageous.

Polyploidy in Crop Improvement: Pros and Cons

Polyploidy has benefits, especially in plants, including hybrid vigour and gene redundancy (Adams and Wendel, 2015). Hybrid vigour in the offspring of two parents results in better health. This is sustained through generations due to paired homologous chromosomes preventing recessive mutations. Gene redundancy protects offspring during the gametophyte life stage, and polyploidy allows for gene function diversification and asexual reproduction. (Woodhouse *et al*., 2009). Polyploidy is essential for plant breeding and agriculture. It helps plants adapt, overcome sterility issues in hybrids and has resulted in social and economic benefits. It is an exciting area of research for agricultural plant evolution and crop diversity (Yali, 2022).

Doubling the genome in a cell can lead to an increase in nucleus volume but only up to a 1.6-fold increase in nuclear envelope surface area. This disrupts interactions between chromosomes and nuclear components, resulting in irregularities during mitosis and meiosis that produce aneuploid cells (Manzoor *et al.,* 2019). Autopolyploids can form multiple homologous chromosome arrangements, leading to abnormal segregation patterns and unbalanced gametes (Bharadwaj, 2015). Changes in gene expression are possible due to increased chromosome copy number and epigenetic instability that affects phenotype and gene expression without changing DNA sequence (Manzoor *et al.,* 2019). Epigenetic instability may result from genomic disturbances caused by polyploidisation, leading to DNA methylation and regulatory changes during the transition to allopolyploidy. Aneuploidy might also play a role in epigenetic remodelling mechanisms observed in allopolyploids (Lloyd and Lister, 2021).

Strategies and Techniques for Polyploidization in the Field of Plant Breeding

Polyploidization is a fundamental technique used in plant breeding that provides a viable solution to infertility and non-viability issues in interspecific hybrids (Zhang *et al*., 2019). Polyploidization creates many new plant varieties with desirable traits like seedlessness, which increases genetic diversity. It also makes plants more resistant to stresses and can produce commercial products. Additionally, it restores fertility in hybrids by addressing genetic imbalances. Polyploidization is essential for modern plant breeding programs to increase yield and quality while minimizing environmental impact (Trojak *et al.,* 2021).

Polyploidization can occur through sexual or somatic methods (Trojak *et al*., 2021). Both methods require careful consideration and experimentation to be successful. One way to achieve polyploidization through somatic means is by using antimitotic agents like colchicines (Manzoor *et al*., 2019), which stops cell division and causes chromosome doubling (Manzoor *et al.,* 2019; Chen *et al.,* 2020). Another way is through sexual polyploidization, where two species are crossed to produce the same result. Although some organisms experience natural sexual polyploidization, genetic manipulation can also facilitate it to produce unreduced gametes. Finally, somatic polyploidization involves exposing cells to antimitotic agents such as colchicine, which doubles chromosomes. This process has various applications in plant breeding, leading to desirable traits such as larger cell size and enhanced vigour (Trojak *et al*., 2021).

Polyploidization is essential for plant diversity and evolution. It affects about 80% of plants. Identifying haplotypes in asexually propagated potatoes can be difficult due to increased Heterozygosity (Hijmans *et al.,* 2007), which hinders researchers' ability to study these plants and understand their genetics and evolution. Polyploidization is important for plants as it creates new genetic combinations that help them adapt and survive in different environments. This also leads to advantages such as pest resistance, drought tolerance, and higher yields, which can assist with crop breeding and agriculture practices. While some asexually propagated plants may have complex haplotype identification, polyploidization is still necessary for plant diversity and evolution. It offers many benefits for agriculture research (Kyriakidou *et al.,* 2018).

Improving crops through polyploidy and hybridization

Crop improvement can be achieved by polyploidy and hybridization, which are key factors. Polyploidy is when an organism has more than two sets of chromosomes, which is crucial for plant evolution. It helps address sterility-related challenges arising from hybridization in agriculture and plant breeding (Wang *et al.,* 2021; Yali, 2022). Crop plants are typically polyploid, with varying degrees of duplication events. However, the benefits of polyploidy remain consistent among all species. Polyploidy protects against genetic disorders and cell death, increases genetic variation, and generates unique phenotypic changes. These benefits make polyploidy attractive for crop improvement projects worldwide (Udall and Wendel, 2006; Stetter *et al*., 2016).

Hybridisation and polyploidy of plants can create new ones with more than two sets of chromosomes. However, studying polyploid crops' genomes is complex due to merging multiple genomes into one nucleus and their large size. Therefore, diploid crops and other model organisms have received more attention in research as they are easier to study (Renny-Byfield and Wendel, 2014). Recent advances in molecular tools like genetic mapping and sequencing offer new insight into growing hybrid plants with desirable traits. Combining specific genes from different parent plants can create new varieties suitable for specific environments or pests while maintaining high yields and nutritional value. This scientific progress unlocks possibilities for crop improvement and enhanced food security (Udall and Wendel, 2006).

Polyploidy can cause loss of chromatin, altered gene expression, new interactions, and endosperm effects. These factors require consideration in a whole-genome context for optimal crop improvement. Wheat is a good example where polyploidy breeding has helped greatly. Triticum wheat's progress in this area is clear due to hybridization and speciation playing a key role. The evolution of polyploid Triticum wheat is ongoing since the domestication of tetraploid emmer wheat caused by natural events rather than discrete cycles at tetraploid and hexaploid levels. (Tejaswi and Talekar, 2021).

Polyploidy and Genomics: Applications and Challenges

Polyploidy alters gene expression by multiplying all chromosomes and uniformly impacting every gene. (Woodhouse *et al*., 2009; Sattler *et al.,* 2016).Some genes may not adhere to the typical pattern due to aneuploidy, resulting in unusual changes in gene expression. Epigenetic modifications found in polyploids, on the other hand, can increase diversity and adaptation by facilitating fast adjustment. These changes at a molecular level could improve plant survival in different environmental conditions and help them thrive despite stressors. However, more research is necessary to thoroughly investigate these findings and their consequences. Woodhouse *et al.,* 2009; Van de Peer *et al.,* 2020).

Breeding polyploid crops is complex due to genome heterozygosity. Marker-assisted selection can improve breeding efficiency, but molecular marker development and analysis for such crops are challenging. Next-generation sequencing technology has become valuable for decoding intricate genomes like octoploid strawberries (Hollister, 2014; Schaart *et al.,* 2021). With this technology comes a better understanding of genome structure and function, which enables the development of new strategies for crop improvement. The result will be increased genetic gain,more productive harvests, and food sustainability (Technologies, 2021).

Editing the genome of polyploid crops is difficult because traditional breeding methods are complicated and time-consuming. Plants also need multiple backcrossing rounds to restore their original genetic composition, leading to inbreeding depression and consuming much time. However, these plants experience quick and consistent structural modifications (Schaart *et al.,* 2021). Therefore, Scientists study resynthesized polyploids to understand genome structure. When editing techniques are applied to crops, changes in physical traits are compared with genetic variations. This helps identify non-functional alleles and better understand trait regulation at the genomic level for improved crop varieties (Doyle and Coate, 2019).

Genome rearrangements and polyploidy pose a significant challenge in editing the genomes of plants (Garg, 2021). Despite the tough cell walls of plants, the CRISPR/Cas system has improved crops by creating genetic variation. Various Cas effectors and editing techniques allow precise DNA modifications, with CRISPR reagents offering multiple options for gene manipulation. Advances in delivering these reagents to plants have been made through various means such as Agrobacterium-mediated delivery, particle bombardment-based delivery, and nanotechnology-based systems. These advances hold promise for future transformations in plant biotechnology. (Li and Xia, 2019; Laforest and Nadakuduti, 2022).

Future of polyploidy: Conclusions and Perspectives

Polyploidy is a well-studied biological process that promotes plant adaptability and speciation. It's essential for crop production, and artificial polyploidy has been developed to enhance crop yields. This process has opened up novel opportunities to identify plants with desired characteristics useful in medicine, horticulture, and pest resistance. Polyploids have several advantages compared to diploid organisms, such as genome buffering, heterozygosity, and heterosis, that increase their vigour. Polyploids also facilitate the transmission of genetic information across different species by restoring the fertility of hybrids and overcoming sterility issues. Overall, polyploidy can lead to the development of novel traits and characteristics that contribute significantly to the overall genetic diversity of the population. Scientists are interested in developing new polyploid varieties that offer superior performance and increased yield potential for global food security challenges while protecting biodiversity.

Over the last few decades, researchers have made significant strides in polyploidy research. With a better understanding of its origins and effects, various aspects of this phenomenon have been studied in depth. As a result, the possibility of boosting crop yields through polyploidy has emerged as a new hope for farmers. To fully capitalize on this discovery, however, there is a need to carry out further research into the complex interactions between genomic alterations, gene expression and regulation. Such studies hold great potential to generate impressive results that can be applied across different domains. As technologies for manipulating polyploid organisms continue to advance, plant breeders will have more opportunities to develop highly productive and desirable crop varieties suited for various purposes.

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