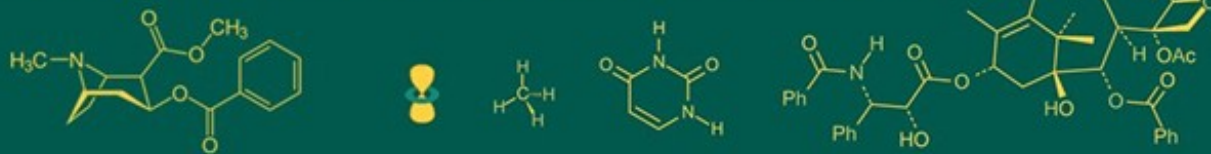


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V Poornima

Phd, Department of Vegetable
 Science Navsari Agricultural
 University Gujarat, India

Deepak

Ph.D. Scholar, Chaudhary
 Charan Singh Haryana
 Agricultural University (CCS
 HAU), Hisar, Haryana, India

Arusha Sharma

Ph.D. Scholar, Department of
 Vegetable Science, CCS
 Haryana Agricultural
 University, Hisar, Haryana,
 India

Utsav Bajal

M.Sc. Scholar, Department of
 Vegetable Science, CCS
 Haryana Agricultural
 University, Hisar, Haryana,
 India

Rohit

M.Sc. Scholar, Department of
 Vegetable Science, CCS
 Haryana Agricultural
 University, Hisar, Haryana,
 India

Corresponding Author:**V Poornima**

Phd, Department of
 Vegetable Science Navsari
 Agricultural University
 Gujarat, India

Polyploidy breeding: Revolutionizing vegetable crop improvement

V Poornima¹, Deepak², Arusha Sharma³, Utsav Bajal⁴, Rohit⁵

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ABSTRACT

Polyploidy, the occurrence of more than two complete sets of chromosomes, has played a pivotal role in plant evolution, diversification, and crop improvement. As a naturally occurring phenomenon as well as an induced breeding strategy, polyploidy has emerged as an important genetic mechanism for generating novel variation and facilitating the development of improved cultivars. In vegetable crops, polyploidization has been widely exploited to broaden the genetic base, overcome reproductive barriers, stabilize interspecific hybrids and enhance breeding efficiency. Recent advances in chromosome manipulation techniques, molecular cytogenetics and genomic approaches have expanded the understanding of polyploid genome organization, gene expression and evolutionary dynamics. The integration of polyploidy into vegetable breeding programmes has created new opportunities for the improvement of economically important traits and the development of resilient cultivars adapted to changing production environments. This review provides a comprehensive overview of the concepts, classification, induction methods, cytological and molecular consequences, and breeding applications of polyploidy in vegetable crops. Furthermore, recent advances, current challenges and future perspectives for the effective utilization of polyploidy in sustainable vegetable improvement are critically discussed.

Keywords: Polyploidy, Advances, Breeding, Genome duplication, Vegetable crops

Introduction

Vegetable crops constitute an indispensable component of human nutrition and play a crucial role in food security, agricultural sustainability and economic development worldwide. The increasing demand for nutritious food, coupled with challenges such as climate change, emerging pests and diseases and shrinking natural resources, necessitates the development of innovative breeding strategies for the production of high-yielding, resilient and nutritionally enhanced cultivars. Among the various approaches employed in crop improvement, polyploidy has emerged as a valuable genetic and breeding tool with profound implications for plant improvement.

Polyploidy, defined as the heritable condition of possessing more than two complete sets of chromosomes, was first described by Winkler (1916) [1] and is widely recognized as a major force shaping plant genome organization and diversification. Approximately 30–70% of angiosperms are estimated to have experienced one or more polyploidization events during their evolutionary history (Chen, 2010; Sattler *et al.*, 2016) [2, 3], highlighting the widespread occurrence and significance of whole-genome duplication in plants. Among the different forms of polyploidy, tetraploidy (4x) is the most prevalent and has been extensively associated with increased genetic variability, phenotypic diversification and crop improvement (Madan *et al.*, 2021) [4].

Whole-genome duplication induces extensive genetic, genomic and epigenetic modifications that alter gene dosage, chromosome behaviour, genome organization and gene expression patterns. These changes generate novel genetic variation and contribute to the expression of desirable agronomic traits. Consequently, polyploid plants often exhibit enhanced cell size, increased biomass accumulation, improved vigour and superior adaptation to diverse environmental conditions, making polyploidization an important mechanism for plant improvement (Can, 2012) [5]. Furthermore, advances in cytogenetics, molecular biology and genomics have expanded the scope of polyploid breeding, enabling more efficient exploitation of polyploid germplasm for the development of superior cultivars.

History

The history of polyploidy research is closely associated with the advancement of cytogenetics, domestication of many crops and plant breeding. The phenomenon gained scientific recognition in the early twentieth century following the introduction of the term polyploidy by Winkler, 1916 [1]. One of the earliest documented examples of chromosome doubling was the naturally occurring tetraploid mutant identified in *Oenothera lamarckiana*, commonly referred to as the “gigas” mutant. Subsequently, chromosome doubling was de-

scribed through the action of colchicine, which laid the foundation for the artificial induction of polyploidy. During the 1940s and 1950s, research efforts increasingly focused on allopolyploidy and interspecific hybridization, emphasizing their significance in crop improvement. Since then, polyploid breeding has been widely employed to develop crops with improved vigour, resilience and adaptability. More recently, advances in genomic research have revealed complex interactions within polyploid genomes that influence gene expression and agronomic performance.

Origin

It has been the subject of several reviews in the last century aimed at explaining the causes and effects of polyploidy (Harlen and de Wet 1975 and Soltis and Soltis 1999) [6].

To explain how polyploids arise naturally in plants, several ideas have been proposed. The two main ways are: Somatic doubling (mitotic nondisjunction) the doubling of chromosomes in non-reproductive cells during the development of the fertilized egg, embryo, or spore-producing tissue, and the formation of reproductive cells with a full set of chromosomes (rather than half) during meiosis (Madlung, 2013; Sattler *et al.*, 2016) [7, 3]. Besides this genetic regulation a variety of environmental factors, have contributed the formation of unreduced gametes including temperature fluctuations, water deficit, physical damage, and nutrient scarcity (Ramsey and Schemske 1998). These unreduced gametes may participate in either bilateral polyploidization (fusion with another unreduced gamete) or unilateral polyploidization (fusion with a reduced gamete) (Sattler *et al.*, 2016) [3]. The cytological mechanisms underlying the production of unreduced gametes are primarily first division restitution (FDR) and second division restitution (SDR). FDR is characterized by the absence of chromosome pairing during zygotene and pachytene, coupled with the non-segregation of homologous chromosomes in anaphase I, resulting in two non-sister chromatids that retain a heterozygosity level comparable to the parental genotype. Conversely, SDR involves the non-separation of sister chromatids in anaphase I, leading to the formation of dyads or triads with a reduced level of heterozygosity relative to the parents. Additional mechanisms contributing to polyploid development in plants include meiotic or mitotic failures, polyspermy (fertilization of the ovum by multiple sperm), and endoreduplication (DNA replication without cytokinesis) (Comai 2005; Song *et al.* 2012; Dar *et al.* 2017) [8, 9]. Chromosome doubling in the zygote or in apical meristems gives rise to complete polyploids and polyploid chimeras, respectively.

Significance of polyploidy

Increased plant vigor and yield

Polyploid plants frequently exhibit the "gigas" effect, characterized by larger plant organs, enhanced vegetative growth, increased biomass accumulation and improved photosynthetic efficiency. These attributes often result in higher productivity and marketable yield. In vegetable crops, polyploidy has been associated with larger fruits, leaves, roots, bulbs and storage organs, thereby improving commercial value (Ramsey *et al.*, 2009) [10].

Improved disease resistance

Polyploidization can enhance resistance to fungal, bacterial, viral and nematode pathogens through increased genetic diversity and the expression of multiple resistance-related genes. Such improvements contribute to reduced disease incidence and lower dependence on chemical control measures.

Enhanced tolerance to abiotic stresses

Polyploid crops often demonstrate superior tolerance to drought, salinity, heat, cold and other environmental stresses. Additional gene copies improve physiological regulation, antioxidant activity and stress-responsive pathways, enabling plants to better withstand adverse environmental conditions.

Improved flavour, texture and nutritional quality

Polyploidy can positively influence sensory and nutritional attributes by increasing the accumulation of sugars, vitamins, minerals, antioxidants and other bioactive compounds. Improvements in flavour, texture, colour, and overall consumer acceptability have been reported in several vegetable crops. Enhanced nutritional quality through increased concentrations of essential nutrients further contributes to their dietary value (Chen *et al.*, 2020) [11].

Types and mechanisms of polyploidy

Autopolyploidy: This arises from the duplication of chromosome sets within a single species, resulting in multiple copies of the same genome. They are also referred as autopolyploids, occur naturally or can be induced artificially through chromosome doubling agents such as colchicine ($C_{22}H_{25}NO_6$), an alkaloid derived from autumn crocus (*Colchicum autumnale*). Autopolyploidy plays an important role in vegetable crop improvement by increasing genome dosage, which often leads to larger plant organ and enhanced vegetative growth. The gigas effect, where autopolyploid individuals have larger roots, leaves, flowers, fruits and seeds compared to their diploid relatives is a common outcome of autopolyploid production (Sattler *et al.*, 2016) [3]. The increased genetic material contributes to greater adaptability, biomass production and physiological resilience through enhanced antioxidant activity and osmotic regulation. In addition, autopolyploidy has been associated with improved salinity tolerance in leguminous crops by enhancing physiological and molecular responses to osmotic and ionic imbalances (Krumenacker, 2023) [12]. However, meiotic irregularities associated with polysomic inheritance may reduce fertility and seed set in some autopolyploid crops.

Advantages of autopolyploidy

- Higher heterozygosity than diploid progenitors due to polysomic inheritance.
- Preservation of more than two alleles per locus.
- Capable of producing a wider range of allozymes than diploids.
- Greater effective population size compared to diploids.
- Selection is more efficient and less influenced by chance-based genetic drift.

Allopolyploidy: Allopolyploids result through interspecific hybridization between two or more genetically distinct species followed by chromosome doubling or by the fusion of unreduced gametes between the species (Acquaah 2007; Chen 2010; Jones *et al.* 2018) [13, 2]. This type of polyploidy is particularly common in Brassicaceae family, where interspecific hybridization has played an important role in crop evolution and diversification. By combining divergent genomes, allopolyploidization facilitates the integration of desirable traits from different species. Genome interactions, gene rearrangements and epigenetic modifications in allopolyploids often generate novel phenotypes, improved adaptability, enhanced stress tolerance and superior agronomic performance. Furthermore, these polyploids can serve as valuable bridging materials for gene transfer, enabling the incorporation of disease resistance, quality traits and environmental resilience from wild relatives into cultivated crops. The resulting fixed heterozygosity and genomic complementation frequently contribute to greater vigor, productivity and evolutionary success compared with their diploid progenitors.

Advantages of allopolyploidy

- Acts as a bridging genotype for transfer of desirable genes across species barriers.
- Combines desirable characteristics from different species.
- Restores fertility in sterile interspecific hybrids through chromosome doubling.
- Exhibits greater vigor and adaptability than parental species, owing to fixed heterozygosity

- Provides increased genetic variability for crop improvement.
- Facilitates the development of new crop species with improved agronomic traits.

Aneuploidy

Aneuploidy refers to a chromosomal variation characterized by the addition or deletion of one or more individual chromosomes from the normal chromosome complement of a species, resulting in chromosome numbers that are not exact multiples of the basic chromosome number. Unlike euploidy, where complete chromosome sets are gained or lost, aneuploidy involves changes in specific chromosomes and is generally caused by irregular chromosome segregation during cell division. Aneuploid individuals arise primarily through meiotic or mitotic non-disjunction, where homologous chromosomes or sister chromatids fail to separate properly, leading to the formation of gametes with extra ($n+1$) or deficient ($n-1$) chromosomes. The occurrence of aneuploidy is particularly common in polyploid species due to the formation of univalents and multivalents during meiosis. These irregular chromosome associations often result in unequal chromosome distribution to daughter cells, producing genetically unbalanced gametes. Following fertilization, such gametes give rise to various aneuploid constitutions.

Ploidy assessment (Saheb *et al.* 2020)

Accurate determination of ploidy level is essential in polyploid breeding programmes. Traditionally, ploidy is confirmed through direct chromosome counting in actively dividing meristematic cells; however, this method is labour intensive, time consuming and requires specialized cytological expertise. Therefore, several indirect and rapid screening methods are commonly employed:

Counting of chloroplast number in stomatal guard cell

An increase in ploidy level is often accompanied by an increase in the number of chloroplasts per guard cell, providing a simple and rapid method for preliminary ploidy determination.

Stomatal measurement

Polyploid plants typically exhibit larger stomata than their diploid counterparts. Measurement of stomatal length and width under a microscope can serve as a useful indicator of ploidy level.

Pollen grain size

An increase in ploidy level is often associated with larger pollen grains. Hence, pollen diameter can be used as a preliminary criterion for identifying polyploids.

Fluorescence In Situ Hybridization

A powerful cytogenetic technique used to detect the presence or absence of specific DNA sequences in chromosome, where by using DNA probes, genetic material can be visualized directly under fluorescence microscope.

Flow cytometry

Rapid and highly accurate technique for estimating thousands of isolated nuclear DNA content and determining ploidy levels. Owing to its precision and efficiency, it has become the most widely used method for ploidy assessment in breeding programmes.

Methods for polyploidy induction

Chemical method

Polyploidization is commonly achieved through the application of antimitotic agents such as colchicine, oryzalin and trifluralin. Among them, colchicine ($C_{22}H_{25}NO_6$) is most widely used alkaloid, derived from *Colchium autumnale* (autumn crocus). It acts by disrupting spindle fiber formation during cell division, preventing chromosome segregation and results in chromosome doubling (Fomicheva *et al.*, 2024) [14]. Colchicine can be applied as aqueous solution, lanolin paste, glycerol or agar formulations to actively dividing tissues. The

efficiency of induction depends on several factors, including the type and concentration of the inducing agent, duration of exposure, explant source, and developmental stage of the plant (Peeters *et al.*, 2024) [15].

Physical method

Genome duplication, PGR mediated induction

In addition to chemical induction, polyploidization can occur through spontaneous genome duplication, which mitigates the need for chemical agents or be facilitated by plant growth regulators that influence the cellular and physiological processes (Hieu, 2023) [16] in vegetable crops, promoting adaptability to environmental stress tolerance.

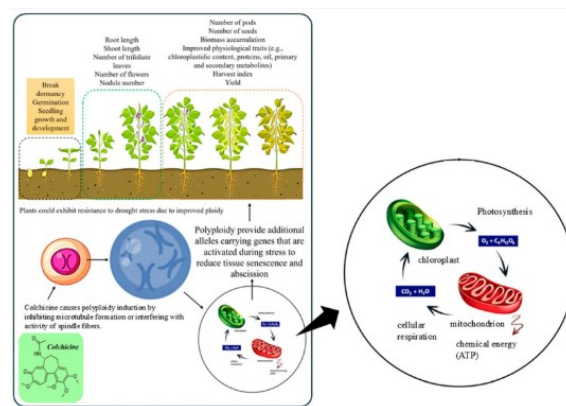


Figure 1. Overview of colchicine-mediated regulation of growth, development and physiological responses in leguminous crops. (Mangena *et al.*, 2023) [17]

Techniques of application

Seed treatment generally employs colchicine concentration ranging from 0.001-1.0% for 1-10 days.

Germinating seedling or invitro derived seedling are used, so that only young shoots are treated with colchicine for 3-24 h.

Growing shoot apices are exposed to 0.1-1.0% colchicine once or twice for several days to induce stable polyploids.

For example, in *Vigna unguiculata* var. *sesquipedalis*, treatment with 0.09 % colchicine for 24 h enhanced pod number, pod weight, seed weight and plant height, while inducing structural chromosomal modifications despite the production of stable polyploids. This highlights the potential of colchicine as a chemical mutagen in generating genetic variability (Fathurrahman *et al.*, 2023) [18].

Consequences associated with polyploidization

Genomic and genetic consequences

Polyploidization results in whole-genome duplication, leading to increased genetic diversity and the generation of novel genetic variation (Sharma *et al.* 2025). Following genome duplication, newly formed polyploids often undergo rapid genomic restructuring, including chromosomal segment loss, gene silencing and diploidization processes that restore diploid-like behaviour (Clarkson *et al.*, 2005; Comai, 2005; Ozkan *et al.*, 2009) [19, 8, 20]. Changes in gene expression may occur without alterations in DNA sequence, influencing plant development and responses to environmental stresses. Over time, redundant DNA sequences may be lost, silenced or converted, contributing to genome stabilization and fertility restoration (Chen *et al.* 2007; Chen, 2010) [2].

Cytogenetic consequences

Polyploidy induces chromosomal modifications such as translocations, deletions and rearrangements that may enhance adaptability and evolutionary potential. Newly formed polyploids often exhibit complex chromosome behaviour before gradually attaining cytological stability through diploidization. Advanced cytogenetic techniques, including flow cytometry and fluorescence in situ hybridization (FISH)

have been widely used to characterize chromosome composition and assess ploidy levels. While these chromosomal changes can improve adaptability and stress tolerance, they may also present challenges associated with genome instability and chromosome pairing behaviour (Sharma *et al.* 2025).

Morphological consequences

Increased nuclear ploidy levels often result in significant morphological changes of plant, resulting in enlarged leaves, flowers, fruits and stomata with increased chloroplast numbers (Fig 7). These characteristics, collectively known as the gigas effect, contribute to enhanced plant vigor and improved organ size in many polyploid crops (Dhawan *et al.*, 1996; Acquaah, 2007) [21, 13].



Figure 2. Comparison between leaf and flower of diploid and induced tetraploid watermelon

Physiological consequences

Genome duplication is accompanied by physiological changes particularly in metabolic activity with increased accumulation of secondary metabolites (Levin, 1983) [22]. Such modifications may enhance plant growth, adaptability and stress tolerance, thereby contributing to improved performance under diverse environmental conditions in vegetable crops.

Applications of polyploidy in vegetable crop improvement

Production of triploid seedless watermelon (*Citrullus lanatus* L.; $3x = 33$)

Triploid watermelon is a seedless type, that has gained significant commercial importance owing to consumer preference for seedless fruits and its dominance in premium markets. The first triploid seedless watermelon ($3n$) was developed in 1947 by Dr. Hitoshi Kihara, major breakthrough in watermelon breeding. Three approaches have been reported for the production of seedless cultivars, including: (i) crossing tetraploid (female parents) and diploid (male parents) (Kihara, 1951; Zhang *et al.*, 2012), (ii) application of plant growth regulators such as cytokinin to pistillate flowers (Hayata *et al.*, 1995) and (iii) pollination of seeded pistillate flowers with sterile pollen grains obtained from seeded cultivars, exposed to X-rays or gamma rays (Sugiyama *et al.*, 2000) [23]. The standard method of creating triploid watermelon production begins with following steps. The first step involves development of tetraploid line ($4n$). To produce tetraploids, diploid plants are treated with colchicine for around 48 h for chromosome doubling. After confirmation of ploidy level in plants with doubled chromosome sets, self-pollination was done to stabilize the tetraploid line (Crow, 1994) [24]. The triploid watermelon seeds are then subsequently produced by crossing a normal diploid melon as pollinator with tetraploid as female parent. During fertilization, each parent contributes half of its respective chromosomes, $1X$ from one parent (diploid) and $2X$ from other (tetraploid) (Wijesinghe *et al.*, 2020) [25], resulting in triploid progeny. Seedless watermelons are becoming more popular with Indian consumers. Through colchicine-induced polyploidy, Kerala Agricultural University (KAU), Thrissur has developed stable tetraploid watermelon line called 'KAU-CL-TETRA-1'. However the developed triploids were highly sterile, they failed to provide sufficient viable pollen for pollination and fruit development, because of irregular chromosome pairing during meiosis.

As a result, diploid pollinizer plants were planted alongside in the same area of triploids in the ratio of 1:2 to supply adequate viable pollen for fruit production, the resulting fruit remain seedless. Triploid watermelons are characterized by excellent fruit quality, superior flavour and good disease resistance. They ship well due to thick rind, improved transportability and a longer shelf life than standard watermelon cultivars.

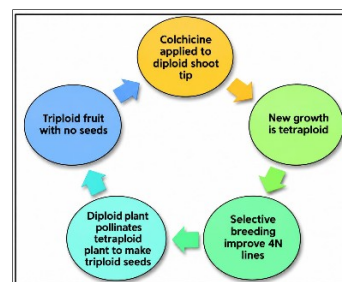


Figure 3. Representation of triploid seedless watermelon production through tetraploid & diploid hybridization

Triploid sugar beet (*Beta vulgaris* L.; $3x = 27$)

Triploid sugar beet is an important polyploid crop cultivated primarily for enhanced sugar production. Sugar beet occurs naturally in diploid ($2x = 18$), triploid ($3x = 27$), and tetraploid ($4x = 36$) forms. Since the 1970s, synthetic triploid cultivars have been widely adopted in Europe and the United States because of their superior agronomic performance. Triploid hybrids are generally produced by crossing diploid male-sterile lines with tetraploid pollinators or through reciprocal crosses (Kinoshita *et al.*, 1969) [26]. Compared with diploid cultivars, triploid sugar beets possess larger storage roots and higher root yield while maintaining comparable sugar content, resulting in increased sugar production per unit area. Furthermore, triploid plants exhibit high sterility and produce few or no viable seeds; however, this does not affect their commercial importance, since the storage root constitutes the economic plant part (Smulders *et al.*, 2010; Dabholkar, 2006) [28, 27].

Contribution of ploidy in evolution of new species

Polyploidization can restore fertility following interspecific hybridization and thereby facilitate the transfer of useful traits across specific barriers.

Amphidiploid Brassica species

Amphidiploids are a class of allopolyploids (tetraploid containing the diploid chromosome sets of both parents). For instance, genus *Brassica* illustrates the evolutionary relationship among three common diploids (*B. oleraceae* CC, $2n = 18$; *B. rapa* AA, $2n = 20$; and *B. nigra*, BB $2n = 16$) and three allotetraploids (*B. juncea*, AABB- $2n = 36$; *B. napus*, AACC- $2n = 38$; and *B. carinata* BBCC- $2n = 34$) derived through hybridization between diploid progenitors followed by chromosome doubling, as depicted below (Fig 3) by *Brassica* U triangle proposed by Nagaharu (1935) [29] (Bellostas *et al.*, 2007; Nelson *et al.*, 2009) [30, 31].

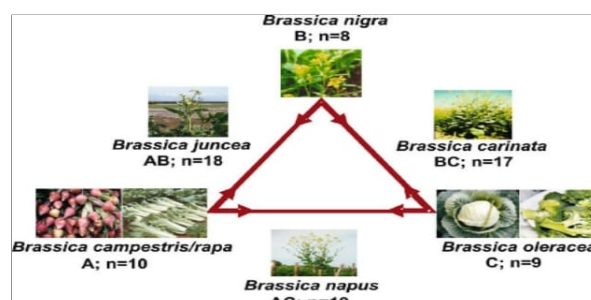


Figure 4. *Brassica* U-triangle, Nagaharu U. (1935) [29]

Raphanobrassica

The synthesis of raphanobrassica ($2n = 4x = 36$) is one of the earliest and well-known example of artificial allopolyploid, developed by Karpencheko (1928) through hybridization between radish (*Raphanus sativus*, $2n = 18$) and cabbage (*Brassica oleracea*, $2n = 18$). The initial F_1 hybrid was sterile due to the absence of homologous chromosome pairing during meiosis. However, spontaneous chromosome doubling restored fertility, resulting in a stable amphidiploid ($2n = 36$). Although the objective was to combine the edible root of radish with the edible leaves of cabbage, the resulting plants possessed radish like leaves and cabbage like roots, limiting their direct commercial value. Nevertheless, Raphanobrassica remains as classic example in the production of fertile allopolyploids. Beyond its historical significance, Raphanobrassica gained importance as intermediate germplasm for introgressing desirable traits such as disease resistance, stress tolerance and forage characteristics into *Brassica* crops.

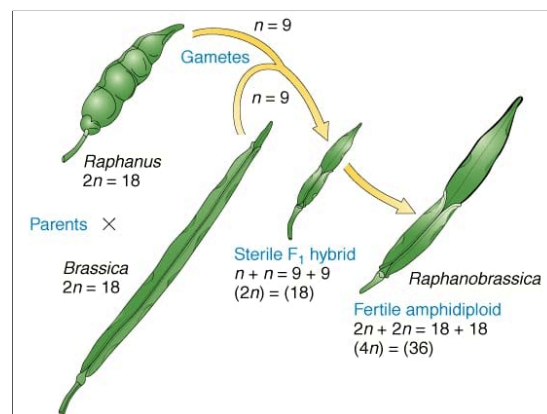


Figure 5. Cytogenic pathway for synthesis of *Raphanobrassica*

Cucumis hytivus: A synthetic amphidiploid cucumber

Interspecific hybridization between *Cucumis hystris* ($2n = 2x = 24$) and *Cucumis sativus* ($2n = 2x = 14$) followed by chromosome doubling, resulted in the development of the synthetic amphidiploid, *Cucumis hytivus* ($2n = 4x = 38$) (Chen *et al.*, 2000) [32]. This amphidiploid serves as an effective genetic bridge for broadening the genetic base and transferring desirable traits from wild germplasm into cultivated cucumber. Subsequent crosses between *C. hytivus* and diploid cucumber produced allotriploid progenies ($2n = 3x = 26$) exhibiting stable chromosome constitution, high parthenocarp and distinct morphological characteristics (Chen *et al.*, 2003) [33], demonstrating their potential in cucumber improvement.

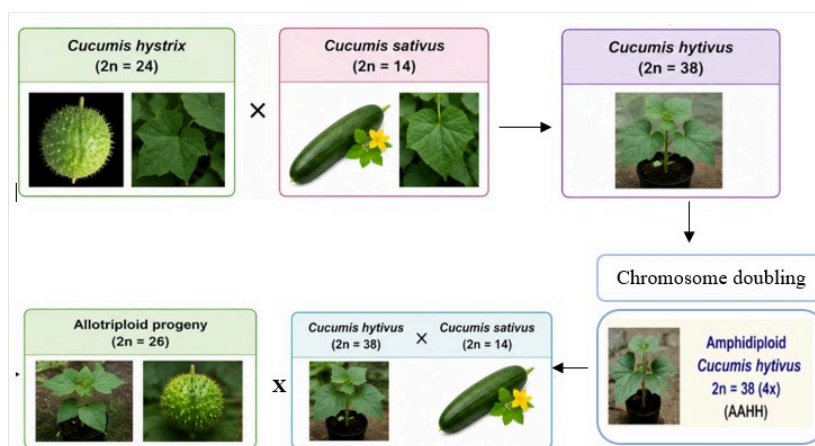


Figure 6. Development of synthetic amphidiploid in cucumber breeding

Table 1. List of polyploidy species in cucumis

Species	2n
<i>C. ficifolius</i>	48
<i>C. heptadactylus</i>	48
<i>C. aculeatus</i>	48
<i>C. figarei</i>	72

Hakuran

It is a synthetic allotetraploid (AACC, $2n = 38$) developed through interspecific hybridization between Chinese cabbage (*Brassica rapa*) and cabbage (*Brassica oleracea*) in Japan in 1966, followed by chromosome doubling to restore fertility. The resulting amphidiploid combined both parental traits, producing juicy, soft heading plants like lettuce with less fibrous leaves suitable for both fresh consumption and pickling. In addition, Hakuran exhibited high resistance to soft rot and other bacterial diseases, along with tolerance to heat and drought stress.

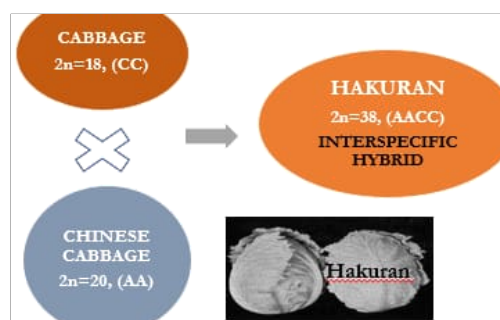


Figure 7. Development of Hakuran

Development of improved cultivars and novel breeding materials

Induced polyploidization has been investigated across diverse vegetable crops, with responses varying according to genotype, induction method and chromosomal constitution. The resulting polyploid genotypes often exhibit distinct morphological, physiological and biochemical characteristics compared with their diploid counterparts. Such variation provides opportunities for selecting breeding materials with desirable traits, including enhanced plant vigour, improved quality and tolerance to environmental stresses. Therefore, polyploidization has been explored not only for altering chromosome number but also for generating novel variation and developing improved breeding materials for vegetable crop improvement. Several examples demonstrating the practical application of this approach and are discussed below

Triploid and tetraploid broad bean (*Vicia faba* L.)

Colchicine mediated chromosome doubling in broad bean achieved by soaking seeds at concentration of up to 4 % for 9-18 hrs resulted in the development of triploid and tetraploid plants. These plants are characterized by altered growth patterns and enlarged stomatal size (Elhaddad *et al.*, 2020) [34].

Polyploid legumes

Induced polyploidy in leguminous vegetables demonstrated improvements in morpho-physiological traits, including enhanced root and shoot growth and greater tolerance to abiotic stresses (drought).

Polyploid onion

The interspecific F₁ hybrid, *Allium cepa* × *Allium fistulosum* and its reciprocal cross developed through chromosome doubling with colchicine resulted in C₂ polyploid population, with superior seedling

vigour and improved winter hardiness better than corresponding diploid plant (McCallum, 1988) [35].

Polyploid garlic

In vitro polyploidization in garlic effectively enhanced genetic variability and improved morphological traits, with the treatment of 0.25 - 0.5% colchicine, immersed for a duration of 24-48 h. Polyploid garlic exhibited desirable characteristics of larger bulb and clove size, thicker leaves, higher chloroplast density and enhanced accumulation of secondary metabolites (Hailu *et al.*, 2021) [36]

Tetraploid asparagus

Tetraploid asparagus was successfully created by treating germinated seeds with 0.15% colchicine and 2% DMSO for 16 h. The induced tetraploids displayed increased vigor, thicker and dark foliage, large stomata with higher number of chloroplasts and chlorophyll content. In addition, elevated antioxidant capacity and reduced oxidative damage contributed to heat tolerance, highlighting the potential of polyploidization for asparagus improvement and stress-resilience (Chen *et al.*, 2020) [37].

Tetraploid red fleshed radish

Red-fleshed radish (*Raphanus sativus* L.) was successfully induced to tetraploid by treating seeds with 0.05% colchicine for 24 h, achieving a tetraploid induction rate of up to 34.5% Chen *et al.* (2021) [38]. The induced tetraploids exhibited both distinct morphological and cytological traits, including enlarged stomata, swollen hypocotyl, larger leaves, flowers, pollen grains, seed pods and taproot along with significantly increased anthocyanin accumulation and pigment yield compared to diploid plants.

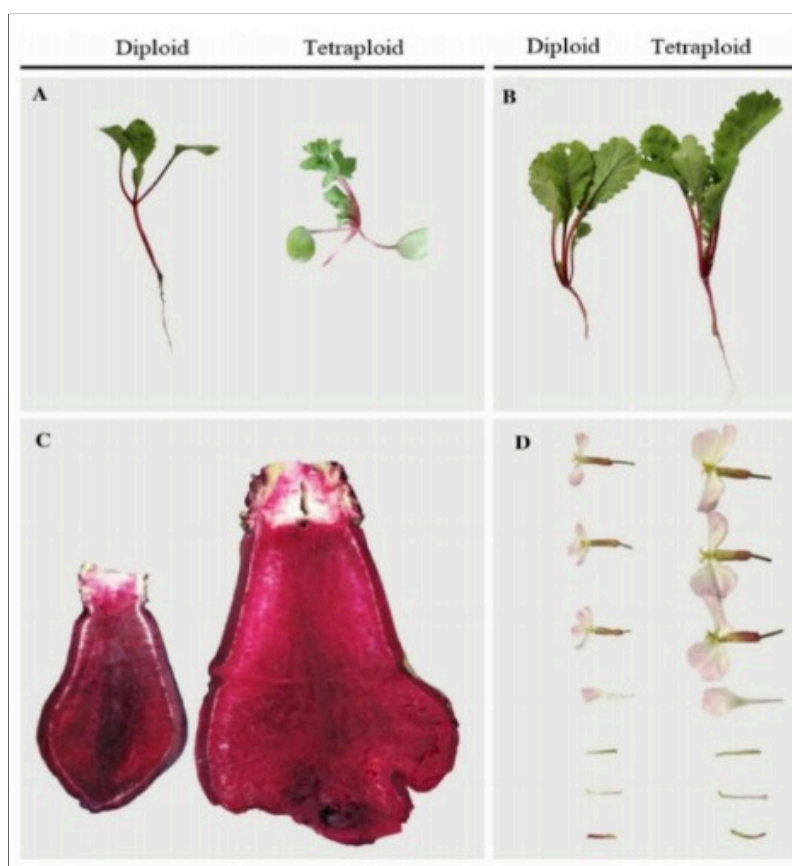


Figure 8. Comparison of seedlings taproot (a,b) and flowers (c,d) between diploids and tetraploids in red flesh radish

Triploid sugarbeet

Sugar beet comes in diploid (18 chromosomes), triploid (27 chromosomes), and tetraploid (36 chromosomes) forms and is a key sugar crop in cooler regions (Smulders *et al.*, 2010) [28]. Triploid sugar beet is made by crossing male sterile diploid plants with tetraploid plants that provide pollen, or by doing the reverse (Kinoshita *et al.*, 1969) [26]. These triploid sugar beets tend to have bigger roots and produce more sugar from a given area (Dabholkar, 2006) [27].

Polyploid lettuce

Polyploid induction in lettuce using colchicine, particularly at lower concentrations (0.1% and 0.3%) improved inflorescence development and promoted first flowering in short duration (19 days), while exces-

sive concentration (0.5 %) delayed flowering, negatively affecting the reproductive performance, thereby indicating the optimized level of colchicine in influencing the inflorescence development (Babura, 2024) [39].

Tetraploid muskmelon

Tetraploid muskmelon developed through colchicine treatment from diploid inbred, M01-3. Tetraploids possessed larger vegetative and floral organs with enhanced chloroplast development and increased soluble sugar, total soluble solids and vitamin C content with approximately 30% greater fruit weight (Zhang *et al.*, 2010) [40]. These desirable traits make tetraploid muskmelon as a valuable breeding material for the development of improved cultivars and seedless triploid hybrids.

Table 2. Representative polyploid crops and their cytogenetic characteristics

Crop species	Nature of occurrence	Type of polyploidy	Chromosome constitution
Potato	Natural	Autopolyploidy	$4x = 48$
Sweet potato	Natural	Autopolyploidy	$6x = 90$
Triploid watermelon	Synthetic	Autopolyploidy	$3x = 33$
Triploid sugarbeet	Synthetic	Autopolyploidy	$3x = 27$
Triploid cassava	Synthetic	Autopolyploidy	$3x = 54$
Leek	Natural	Autopolyploidy	$4x = 32$
Yam	Natural	Autopolyploidy	$3x = 60; 4x = 80$

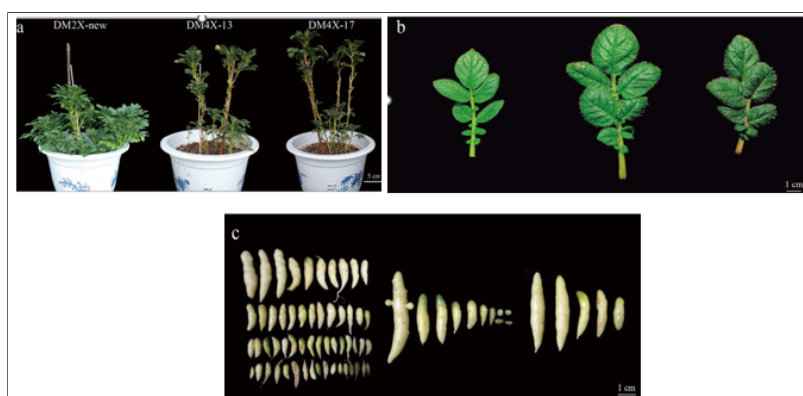
Tetraploid turnip

Tetraploid turnip exhibited superior salinity tolerance compared with its diploid progenitor under 200 mmol L⁻¹ NaCl stress. The improved stress adaptation was attributed to better ionic regulation, reflected by a higher root K⁺/Na⁺ ratio, coupled with increased glutathione content and antioxidant activity (Hua-bing *et al.*, 2011) [41].

Tetraploid lines of potato

Whole-genome doubling in potato resulted in the development of homozygous tetraploid lines with distinct morphological and physiological alterations, including increased plant height, stem diameter, leaf

size and tuber weight compared with diploids. The tetraploid lines exhibited reduced accumulation of reducing sugars during cold storage, indicating enhanced resistance to cold-induced sweetening. Furthermore, altered gene expression and enrichment of the active histone modification H3K27ac, with genome-wide analyses highlighted the role of epigenetic regulation in enhancing stress tolerance and storage quality of tetraploid potatoes (Guo *et al.*, 2023) [42].

**Bridge crossing**

Bridge crossing is a breeding strategy that utilizes polyploidy to overcome reproductive barriers between sexually incompatible species. In this approach, chromosome doubling is employed to restore fertility in sterile interspecific hybrids, facilitating gene transfer between related species. Polyploid bridge species serve as intermediates for the introgression of desirable traits such as disease resistance, abiotic stress tolerance and improved quality attributes into cultivated crops. This approach has been successfully employed in several vegetable crops such as tomato, eggplant, potato and brassicas to exploit valuable genes from wild relatives into cultivated varieties.

Exploitation of polyploidy in modern breeding approaches**Mutation breeding**

Polyploidy enhances the efficiency of mutation breeding by increasing genetic redundancy and buffering the deleterious effects of induced mutations. The presence of multiple gene copies allows polyploids to tolerate mutational changes that might otherwise be lethal in diploid genomes. Furthermore, chromosome doubling increases genome size and the number of mutational targets, resulting in a higher frequency of induced mutations. Consequently, the integration of induced polyploidization in combination with mutagenesis has been widely exploited for the development of crop genotypes, possessing improved agronomic performance.

Molecular marker-assisted and genomic breeding

Molecular markers have become indispensable tools for the characterization and utilization of polyploidy in vegetable crop improvement. Marker systems such as RAPD, AFLP, ISSR, SSR and SNPs are widely employed for genetic diversity analysis, ploidy verification, cultivar identification and marker-assisted selection in polyploid breeding populations. These approaches facilitate the detection of genomic variation associated with polyploidization and enable the efficient selection of superior genotypes. In tetraploid potato (*Solanum tuberosum*), SNP-based markers and linkage mapping have been extensively utilized for quantitative trait locus (QTL) identification and marker-assisted breeding for late blight resistance and other complex

agronomic traits. Similarly, molecular marker analyses have been employed in sweet potato (*Ipomoea batatas*) to characterize polyploid germplasm and identify genomic regions associated with β -carotene accumulation, storage root quality and stress tolerance. In brassica vegetables, SSR and SNP markers have been used to assess genetic diversity and genome composition in polyploid breeding materials. Convergence of molecular marker technologies and next-generation sequencing revolutionized polyploid breeding by facilitating high-resolution genome characterization, accurate detection of genetic variation, and efficient identification of loci governing economically important traits, thereby accelerating the development of improved cultivars.

Table 3. Polyploidy varieties of vegetable crops and their salient features

Crop	Variety	Features
Palak	Pusa Jyothi	Tetraploid variety with thick, tender and dark green foliage with quick regeneration capacity.
Cassava	Sree Harsha	Triploid, stout and non-branching variety with high starch content of 39.05 %
Cassava	Sree Athulya	Triploid branching hybrid with greyish brown stout stem and higher starch content (30.2%). Field tolerance to cercospora leaf spot, scale insect and spider mites.
Cassava	Sree Apporva	Triploid tall branching hybrid with stout stem, yellowish brown in colour with high extractable starch (29.9%). Field tolerance to cercospora leaf spot, scale insects.
Watermelon	Arka Madhura	Triploid seedless variety suitable for year round production under protected condition with TSS of 13-14 %, exhibiting extended shelf life and transport quality.
Watermelon	Pusa Bedana	Triploid seedless watermelon hybrid with aborted embryos and rudimentary seeds with red flesh and TSS of 12-13 %
Watermelon	Swarna	Red fleshed triploid seedless hybrid, developed by crossing KAU-CL-TETRA 1 x CL-4, with dark green rind colour and light green stripes.
Watermelon	Shonima	Yellow fleshed triploid seedless hybrid developed by crossing KAU-CL-TETRA 1 x CL-5, with green colour rind and yellow stripes.

Limitations in polyploidy breeding

Reduced fertility

Odd number chromosome genotypes cannot divide evenly during meiosis, resulting in unbalanced non-viable gametes, causing sterility.

Poor adaptability

Although polyploidy may confer stress tolerance in some cases, newly synthesized polyploids exhibit reduced ecological fitness and inconsistent environmental adaptation.

Cytogenetic instability

Chromosome mispairing and genomic alterations can limit genetic stability.

Complexity in breeding

Complex inheritance patterns, polysomic chromosomal behaviour and difficulties in trait fixation make breeding in polyploid crops challenging.

Conclusion

Polyploidy has emerged as an important breeding strategy for vegetable crop improvement, contributing to increased genetic variability and the development of cultivars with superior agronomic performance. Through genome duplication and chromosome manipulation, polyploid plants often exhibit enhanced agronomic traits including yield potential, organ size, better quality attributes and increased tolerance to biotic and abiotic stresses. The successful application of polyploidy in several vegetable crops, particularly for the development of seedless varieties and improved nutritional and market traits, highlights its significance in modern breeding programs. In addition,

polyploidy facilitates the utilization of diverse genetic resources and broadens the scope for crop improvement. Despite challenges such as reduced fertility and chromosomal instability in some polyploid forms, its overall contribution to vegetable breeding remains substantial. The widespread occurrence and successful exploitation of polyploidy in vegetable crops demonstrate its value as a reliable approach for developing productive, resilient and high-quality cultivars suited to diverse growing conditions and consumer preferences.

Future prospects

Future research should focus on integrating polyploidization with advanced genomic and molecular breeding approaches to improve the efficiency and predictability of vegetable crop improvement. Greater emphasis on the development of stable polyploid genotypes with enhanced yield, quality and stress tolerance, together with overcoming fertility and chromosome instability, which will facilitate their wider utilization in breeding programmes.

References

- Winkler H. About the experimental production of plants with different chromosome numbers. *Zeitschrift für Botanik*. 1916;8:417-531.
- Chen ZJ. Molecular mechanisms of polyploidy and hybrid vigour. *Trends Plant Sci*. 2010;15(2):57-71.
- Sattler MC, Carvalho CR, Clarindo WR. The polyploidy and its key role in plant breeding. *Planta*. 2016;243:281-296.
- Madan H, Escrib A, Hosseini B, Sanchez-Munoz R, Khojasteh A, Palazon J. Effect of polyploidy induction on natural metabolite production in medicinal plants. *Biomolecules*. 2021;11(6):899.
- Can S. Polyploid organisms. *Sci. China Life Sci*. 2012;55(4):301-311.

6. Harlan JR, de We MJM. On O. Winge and a prayers: The origins of polyploidy. *Bot Rev.* 1975;41(4):361-390.
7. Madlung A. Polyploidy and its effects on evolutionary success: Old questions with new tools. *Heredity.* 2013;110:99-104.
8. Comai L. The advantages and disadvantages of being polyploid. *Nat Rev Genet.* 2005;6(11):836-846.
9. Song C, Lin X, Xiao J, He W, Zhao Y, Qin Q, Zhang C, Liu Y. Polyploid organisms. *Sci China Life Sci.* 2012;55:301-311.
10. Ramsey J, Schemske DW. Pathways to polyploidy in flowering plants. *Annu Rev Ecol Evol Syst.* 2009;40(1):517-541.
11. Chen ZH, Chen LJ. Polyploidy and its impact on fruit quality in plants. *Front Plant Sci.* 2020;11:1232.
12. Krumenacker Y. Cell mutagenic autopolyploidy enhances salinity stress tolerance in leguminous crops. 2023.
13. Acquaaah G. Principles of Plant Genetics and Breeding. Malden, MA, USA: Blackwell Publishing; 2007.
14. Fomicheva M, Kulakov Y, Alyokhina K, Domblides E. Spontaneous and chemically induced genome doubling and polyploidization in vegetable crops. *Horticulturae.* 2024;10(6):551.
15. Peeters MK, Maryns I, Ghesquiere A, Van Laere K, Van de Peer Y, Ruttink T, Leus L. Optimized tetraploidization strategies in tissue culture for *Lolium*, *Festuca* and *Festulolium*. *Biol Plant.* 2024;68:70-76.
16. Hieu PV. Evolutionary fixed potential agronomic traits in polysomic polyploidy plants with special reference to potato. *Am J Plant Sci.* 2023;14(7):793-811.
17. Mangena P, Mushadu PN. Colchicine-induced polyploidy in leguminous crops enhances morpho-physiological characteristics for drought stress tolerance. *Life.* 2023;13(10):1966.
18. Fathurrahman F, Mardaleni M, Krisianto A. Effect of colchicine mutagen on phenotype and genotype of *Vigna unguiculata* var. *sesquipedalis* the 7th generation. *Biodiversitas.* 2023;24(3):1408-1416.
19. Clarkson JJ, Lim KY, Kovarik A, Chase MW, Knapp S, Leitch AR. Long term genome diploidization in allopolyploid *Nicotiana* section *Repandae* (Solanaceae). *New Phytol.* 2005;168(1):241-252.
20. Ozkan H, Feldman M. Rapid cytological diploidization in newly formed allopolyploids of the wheat (*Aegilops-Triticum*) group. *Genome.* 2009;52(11):926-934.
21. Dhawan O, Lavania UC. Enhancing the productivity of secondary metabolites via induced polyploidy: A review. *Euphytica.* 1996;87(2):81-89.
22. Levin D. Polyploidy and novelty in flowering plants. *Amer Naturalist.* 1983;122(1):1-25.
23. Sugiyama K, Morishita M. Production of seedless watermelon using soft-X-irradiated pollen. *J Japan Soc Hort Sci.* 2000;69(6):684-89.
24. Crow JF. Hitoshi Kihara, Japan's pioneer geneticist. *Genetic.* 1994;137:891-894.
25. Wijesinghe SAEC, Evans LJ, Kirkland L, Rader R. A global review of watermelon pollination biology and ecology: The increasing importance of seedless cultivars. *Sci Hortic.* 2020;271:109493.
26. Kinoshita T, Takahashi M. Studies in polyploid varieties of sugar beets: Use of cytoplasmic male sterility in the production of triploid hybrids and their performance in trials. *J Fac Agric.* 1969;56(2):171-186.
27. Dabholkar AR. General plant breeding. New Delhi: Concept Publishing Company; 2006.
28. Smulders MJ, Esselink GD, Everaert I, De-Riek J, Vosman B. Characterization of sugar beet (*Beta vulgaris* L. ssp. *vulgaris*) varieties using microsatellite markers. *BMC Genetics.* 2010;11:41-52.
29. Nagaheru U. Genome analysis in *Brassica* with special reference to the experimental formation of *B. napus* and peculiar mode of fertilization. *J Jap Bot.* 1935;7:389-452.
30. Bellostas N, Sorensen AD, Sorensen JC, Sorensen H. Genetic variation and metabolism of glucosinolates. *Adv. Bot. Res.* 2007;45:369-415.
31. Nelson MN, Mason AS, Castello MC, Thomson L, Yan G. Microspore culture preferentially selects unreduced (2n) gametes from an interspecific hybrid of *Brassica napus* L. x *Brassica carinata* Braun. *Theor Appl Genet.* 2009;119:497-505.
32. Chen JF, Kirkbride JJ. A new synthetic species of *Cucumis* (Cucurbitaceae) from interspecific hybridization and chromosome doubling. *Brittonia.* 2000;52:315-31.
33. Chen JF, Luo XD, Stau JE, Ren G. An allotriploid derived from an amphidiploid x diploid mating in *Cucumis*. *Euphytica.* 2003;131(2):235-241.
34. Elhaddad N, Blash K, Khatab H. Phenotypic and molecular characterization of polyploidy *Vicia faba* induced by colchicine. *GSC Biol Pharm Sci.* 2020;11(3):235-243.
35. McCollum GD. Amphidiploid onion germplasm FC 8407 and FC 8432. *HortSci.* 1988;23(5):918-919.
36. Hailu MG, Mawcha KT, Nishimiyama S, Suharsono S. Garlic micro-propagation and polyploidy induction in vitro by colchicine. *Plant Breed Biotech.* 2021;9(1):1-19.
37. Chen H, Lu Z, Wang J, Chen T, Gao J, Zheng J, Zhang S, Xi J, Huang X, Guo A, Yi K. Induction of new tetraploid genotypes and heat tolerance assessment in *Asparagus officinalis* L. *Sci Hortic.* 2020;264:109-168.
38. Chen F, Gao J, Li W, Liu Y, Fang P, Peng Z. Colchicine-induced tetraploidy influences morphological and cytological characteristics and enhances accumulation of anthocyanins in a red-fleshed radish (*Raphanus sativus* L.). *Hortic. Environ. Biotechnol.* 2021;62(6):937-948.
39. Babura SR. Effect of polyploidy induction in lettuce (*Lactuca sativa*) through colchicine treatment: Implications for inflorescence and flowering. *Biol. Environ. Sci. J. Trop.* 2024;21(1):207-212.
40. Zhang W, Hao H, Ma L, Zhao C, Yu X. Tetraploid muskmelon alters morphological characteristics and improves fruit quality. *Sci Hortic.* 2010;125(3):396-400.
41. Hua-bing M, Si-Si J, Shui-jin H, Xian-yong L, Yuan-long L, Wan-li G, Li-xi J. Comparison between a tetraploid turnip and its diploid progenitor (*Brassica rapa* L.): The adaptation to salinity stress. *Agric Sci China.* 2011;10(3):363-375.
42. Guo H, Zhou M, Zhang G, Li H, Yan C, Wan M, Hu J, He W, Zeng D, Zhu B, Zeng Z. Development of homozygous tetraploid potato and whole genome doubling-induced enrichment of H3K27ac potentially enhanced resistance to cold-induced sweetening in tubers. *Hortic Res.* 2023;10(3):uhad017.
43. Chen ZJ, Ha M, Soltis D. Polyploidy: Genome obesity and its consequences: Polyploidy workshop: Plant and animal genome XV conference, San Diego, CA, USA. *New Phytol.* 2007;174(4):717-720.
44. Dar J, Beigh Z, Wani AA. Polyploidy: Evolution and crop improvement. In *Chromosome Structure and Aberrations*. Springer. 2007:1-22.
45. Kihara H, Nishiyama I. An Application of Sterility of Autotriploids to the Breeding of Seedless Water Melon. *Seiken Zihō.* 1947;3:93-103.
46. Saheb Pal, Solanki Bal. Polyploidy: a novel technique for improvement of vegetable crops. *Agriculture and Food: e-Newsletter.* 2020;2(2):Article 22863.
47. Sattler MC, Carvalho CR, Clarindo WR. The polyploidy and its key role in plant breeding. *Planta.* 2016;243:281-296.

48. Soltis DE, Soltis PS. Polyploidy: Recurrent formation and genome evolution. *Trends in Ecology & Evolution*. 1995;10:148-153.

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