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PARTHENOCARPY AND ITS EFFECT ON VEGETABLE FRUITS QUALITY: A REVIEW

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ABSTRACT

Parthenocarpy is considered one of the most effective strategies for fruit production under unfavorable environmental conditions that hinder pollination and fertilization. Extreme temperatures, whether excessively low or high, negatively affect pollen production and viability, often requiring external intervention for successful fruit set. This review aimed to evaluate the effects of parthenocarpy on various vegetable crops cultivated in Afghanistan. Recent studies have compared the performance of parthenocarpic vegetable fruits with their pollinated counterparts. Findings indicate that key phytohormones, including gibberellins, cytokinins, and auxins, play a crucial role in fruit development in the absence of pollination. In conclusion, parthenocarpy in fruit vegetables leads to the production of seedless fruits and pods, enhances fruit set, increases yield, improves fruit quality, increases total soluble solids, extends shelf life, ensures uniformity, and can result in smaller, lighter fruits while increasing the number of fruits per plant. Additionally, in certain fruit vegetables, parthenocarpy can affect fruit shape, flavor, and β-carotene metabolism during storage. To optimize productivity and quality, it is recommended to use appropriate methods and phytohormones, depending on the available infrastructure.

Key words: cucumber, muskmelon, pointed gourd, pumpkin, squash, okra

INTRODUCTION

Parthenocarpy refers to the process of seedless fruit formation from the ovary without pollination or fertilization (Su et al. 2021; Indian et al. 2023; Maupilé et al. 2024; Chaudhari et al. 2024). A fruit completely devoid of seeds, containing only rudimentary or immature seeds, or exhibiting embryonic abnormalities is considered as parthenocarpic (Indian et al. 2023; Baddigam et al. 2024). Parthenocarpy was first noted in the late 19th century by Sturtevant. Later, the occurrence of seedless tomato plants (*Solanum lycopersicum* L.) was reported by Hawthorn (Sharif et al. 2022). The term "parthenocarpy" was introduced in 1902 by Noll, derived from the Greek words *parthenos* (virgin) and *carpy* (fruit). Then, in 1908, Winkler provided a formal definition of parthenocarpy (Baddigam et al. 2024; Chaudhari et al. 2024).

Parthenocarpy can occur naturally or be induced artificially through the use of hormones or by increasing endogenous hormone levels (Chaudhari et al. 2024). The development of parthenocarpy in vegetables influenced by both genetic and environmental factors. Some cultivars exhibit this trait naturally, while others require specific conditions, such as temperature and light, to induce parthenocarpy (Chaudhari et al. 2024).

The primary causal factors of parthenocarpy include lack of pollination, unsuccessful fertilization despite pollination, or fertilization with subsequent embryo (seed) abortion – all of which contribute to

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the formation of parthenocarpic fruits (Indian et al. 2023). Lack of pollination can result from male sterility, self-incompatibility, or unfavorable environmental conditions (Patel et al. 2022; Chaudhari et al. 2024). The biological basis of parthenocarpy allows fruit development without fertilization, bypassing the conventional role of seeds in hormone production. Typically, seed formation triggers phytohormone-driven processes that stimulate fruit growth (Baddigam et al. 2024). However, in parthenocarpic fruits, alternative hormone sources, genetic alterations, or increased hormone sensitivity can induce ovary development (Patel et al. 2022).

Parthenocarpic fruit development is often influenced externally by the use of plant growth regulators, including auxins – 2,4-dichlorophenoxyacetic acid (2,4-D) and naphthaleneacetic acid (NAA), cytokinins – N-(2-chloro-4-pyridyl)-N′-phenylurea (CPPU), gibberellic acids (GA_3), and brassinosteroids. Ethylene and melatonin have also been reported to play a regulatory role in parthenocarpy (Sharif et al. 2022).

The development of parthenocarpic cultivars involves selecting and breeding plants with specific genetic traits that promote fruit set without fertilization. These traits can occur naturally or be introduced through genetic engineering techniques (Chaudhari et al. 2024). Several studies have shown that parthenocarpic plants can perform better under both biotic and abiotic stress conditions compared to those requiring fertilization (Sharif et al. 2022). Thus, parthenocarpy is considered one of the most effective fruit production strategies in environments where pollination and fertilization are suboptimal (Indian et al. 2023). Parthenocarpic vegetables provide higher yields even under poor pollination or challenging climatic conditions, producing uniform, seedless, and marketable fruit. Parthenocarpy enables year-round greenhouse cultivation, shortens the maturation period, increases food security by improving resilience to climate change, and contributes to more sustainable and adaptable agriculture (Chaudhari et al. 2024).

Seedless fruit is preferred in some vegetables due to its better texture, desirable flavor, and lower allergenic content (Patel et al. 2022). This phenomenon has been reported in cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena* L.), watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai), and tomato, increasing consumer appeal while also posing a research challenge for improving fruit quality and productivity (Patel et al. 2022; Baddigam et al. 2024). In some crops, such as eggplant, seedlessness can improve fruit quality. However, in dioecious plants such as kiwifruit, parthenocarpy increases yields by eliminating the need for pollinizer plants (Indian et al. 2023).

Interest in parthenocarpic traits in horticultural crops is growing due to their potential to improve fruit quality, increase plant resilience, and reduce preharvest fruit drop. Seedless fruits are highly attractive to consumers because they contain more edible flesh, and larger mesocarp tissue replaces seeds and seed cavities. These attributes make such fruits ideal for processing into jellies and other products (Sharif et al. 2022). Parthenocarpy also improves fruit quality and shelf life, as observed in eggplant. Seedless vegetables, such as parthenocarpic tomatoes, often have better flavor and higher soluble solids content (Patel et al. 2022; Baddigam et al. 2024). Moreover, parthenocarpy increases processing efficiency and profitability by eliminating the need for seed removal. It also addresses challenges associated with the approval of transgenic crops and prevents horizontal gene transfer in genetically modified plants (Indian et al. 2023). Overall, parthenocarpy significantly improves fruit quality (Sharif et al. 2022).

However, parthenocarpy can also exert adverse effects, including the development of misshapen, smaller, or softer fruits. It can also reduce biodiversity and weaken plant disease resistance (Chaudhari et al. 2024). Gene flow from seedless crops can induce sterility in nonengineered plants. Furthermore, premature auxin application before anthesis can damage flowers, induce seed abortion, and cause fruit abscission (Chaudhari et al. 2024).

Low yield, poor fruit quality, and short storage life are major challenges for fruit vegetables. In addition, the presence of seeds in some vegetable fruits, which can result in enormous fruit size, is often undesirable for consumers. This review aims to explore seedless fruit production methods in vegetable crops, assess the impact of their production on fruit yield and quality, and provide better guidance for farmers. The study was conducted by reviewing research published in national and international journals between 2012 and 2025. Only credible sources were collected, thoroughly analyzed, and synthesized in this comprehensive review article.

TYPES OF PARTHENOCARPY

Generally, there are two types of parthenocarpy – natural or artificially induced by exogenous application of hormones or some other mechanisms (Indian et al. 2023; Baddigam et al. 2024; Chaudhari et al. 2024).

Natural or genetic parthenocarpy

Parthenocarpy occurs when its expression is either independent of external factors or triggered under conditions unfavorable for pollination and fertilization (Patel et al. 2022; Baddigam et al. 2024). Elevated levels of endogenous hormones in the ovary can induce natural parthenocarpy even in the absence of pollination or fertilization (Patel et al. 2022; Baddigam et al. 2024). This phenomenon has been documented in crops such as tomato, eggplant, cucumber, and sweet pepper (*Capsicum annuum* L.) (Dhatt & Kaur 2016; Patel et al. 2022; Indian et al. 2023; Chaudhari et al. 2024). Genetic parthenocarpy can mitigate challenges such as low pollen viability and inadequate pollen release, which often arise under conditions of low light and extreme temperatures, both in the field and in greenhouses (Dhatt & Kaur 2016; Patel et al. 2022).

Obligate parthenocarpy occurs due to the prevention of pollination (Indian et al. 2023; Chaudhari et al. 2024).

Facultative parthenocarpy results from genetic sterility (continuous vegetative propagation) and is triggered by elevated levels of endogenous hormones in the ovary, as well as unfavorable conditions for pollination and fertilization. This has been observed in crops such as tomato, eggplant, and pineapple (Indian et al. 2023; Baddigam et al. 2024; Chaudhari et al. 2024). A single, incompletely dominant gene responsible for this form of parthenocarpy has been identified (Baddigam et al. 2024). Facultative parthenocarpy occurs only in the absence of pollination and fertilization (Dhatt & Kaur 2016).

Vegetative/autonomic parthenocarpy does not require any external stimulus and can observed in crops such as Washington navel orange, oriental persimmon, cucumber, and banana (Indian et al. 2023; Chaudhari et al. 2024).

Stimulative parthenocarpy requires pollination or another stimulus for fruit production. Examples include ‘Black Corinth’ grape, blackberry, and pear (Indian et al. 2023; Chaudhari et al. 2024).

Stenospermocarpy occurs when pollination and fertilization take place, but the embryo is aborted. This is observed in the ‘Thompson’ seedless grape and the ‘Sindhu’ mango (Indian et al. 2023; Chaudhari et al. 2024).

Artificial parthenocarpy

Artificial parthenocarpy involves inducing fruit development in the absence of pollination or fertilization through human-mediated techniques (Patel et al. 2022; Indian et al. 2023; Chaudhari et al. 2024). Application of irradiated pollen, natural or synthetic auxins, and gibberellic acid (GA_3) increases indole-3-acetic acid (IAA) levels during ovary development, thereby increasing the levels of endogenous phytohormones that promote parthenocarpic fruit formation, independent of seed development (Dhatt

& Kaur 2016; Patel et al. 2022). Nitsch (1970) defined a plant as parthenocarpic when the concentration of growth regulators exceeds a critical threshold during anthesis (Dhatt & Kaur 2016; Patel et al. 2022). In eggplant, IAA levels rise during the first five days after anthesis, reaching a significant peak around day 20 in both pollinated and auxin-treated flowers (Dhatt & Kaur 2016; Patel et al. 2022).

Several approaches can be used to induce artificial parthenocarpy, including the use of plant growth regulators, distant hybridization, mutagenesis, irradiated pollen, modifications of chromosome number, gene silencing, targeted genetic modifications, and genome editing (Indian et al. 2023; Baddigam et al. 2024; Chaudhari et al. 2024).

Plant hormone use

Gibberellins, cytokinins, and auxins can induce parthenocarpy. However, when parthenocarpic fruits are treated with other plant growth regulators, such as 2,3,5-triiodobenzoic acid (TIBA), CPPU, or 2,4-D, they often develop hollow seeds enclosed in a thin, soft, and edible coating (Hassan & Miyajima 2019; Cong et al. 2020; Baddigam et al. 2024; Chaudhari et al. 2024; Maupilé et al. 2024; Meng et al. 2024).

Hybridization

Breeding populations exhibiting parthenocarpic traits can be developed through distant hybridization. Interspecific hybridization has been successfully used to generate facultative parthenocarpic lines. Furthermore, altering ploidy levels through interspecific hybridization is a common strategy for producing parthenocarpic fruit in crops such as watermelon, tomato, and banana (Baddigam et al. 2024; Chaudhari et al. 2024).

Mutation

Spontaneous mutations can arise naturally or be artificially induced. They can involve signaling pathways, hormone synthesis, fruit development, or classical breeding programs, ultimately triggering the formation and growth of parthenocarpic fruits (Baddigam et al. 2024; Chaudhari et al. 2024).

Irradiated pollen

Various doses of pollen irradiated with X-rays or γ-rays can be used to obtain seedless fruit (Baddigam et al. 2024; Chaudhari et al. 2024).

Chromosome number change

The imbalance in embryo and endosperm development in a triploid background has been exploited to produce parthenocarpic fruit (Baddigam et al. 2024). In some crops, seedless fruit arise from F_1 hybrid plants derived from crosses between tetraploid and diploid parents, resulting in triploid progeny that produce seedless or nearly seedless fruit. For instance, colchicine is used to induce polyploidy in watermelon, and when a tetraploid maternal parent is crossed with a diploid paternal parent, the resulting triploid plants produce fruit containing very few seeds (Hassan et al. 2020; Baddigam et al. 2024; Chaudhari et al. 2024).

Gene transfer and silencing

Genetic engineering techniques can be used to induce parthenocarpy. Seedless fruit development can be achieved by introducing genes involved in hormonal signaling pathways, auxin biosynthesis, or other regulatory mechanisms. Although parthenocarpic traits have been successfully introduced into transgenic plants such as tobacco (*Nicotiana tabacum* L.), eggplant, and tomato, in some cases this has resulted in undesirable phenotypes (Kim et al. 2019; Baddigam et al. 2024).

One of the most notable cases of parthenocarpy induced by the *MCM-AGAMOUS-DEFICIENS-SRF* (MADS)-box-related gene involves *AGAMOUS-LIKE 6* (*AGL6*). Suppression of *AGL6* leads to facultative parthenocarpy. In transgenic tomato plants, this modification allows normal fruit development with seeds upon pollination, whereas under unfavorable conditions, the plants produce seedless fruits (Molesini et al. 2020).

FACTORS AFFECTING PARTHENOCARPY

Genetic factors

Certain plant species naturally harbor genes that promote parthenocarpy, allowing fruit development without pollination or fertilization. These genes regulate the synthesis of hormones such as auxins and gibberellins, which are crucial for fruit formation. Mutations or modifications in these genes can induce parthenocarpy. In tomato, for instance, the *SlAGAMOUS-LIKE 6* (*SlAGL6*) gene has been identified as a key regulator, with mutations resulting in the production of seedless fruit (Chaudhari et al. 2024; Ganvit et al. 2024).

Hormonal factors

Natural parthenocarpy can result from hormonal imbalances in the plant, with auxins, gibberellins, and cytokinins playing a central role in fruit development. Auxins, particularly IAA, are crucial for fruit initiation and growth, and elevated auxin levels in the ovary can, in some cases, trigger fruit development in the absence of fertilization. Ethylene also affects parthenocarpy, promoting fruit growth and ripening. Its application can induce parthenocarpic fruit formation in specific species. Additionally, abscisic acid (ABA) affects fruit development and may contribute to the induction of parthenocarpy (Dhatt & Kaur 2016; Joldersma & Liu 2018; Liu et al. 2018; Cong et al. 2020; Su et al. 2021; Chaudhari et al. 2024; Ganvit et al. 2024; Maupilé et al. 2024).

Environmental factors

Environmental conditions also play a critical role in the occurrence of parthenocarpy. Factors such as temperature, light, and water availability can significantly influence fruit development. Extreme temperatures, high humidity, low light intensity, heavy rainfall, and strong winds can adversely affect various stages of the reproductive process, including pollen formation, dispersal, germination, fertilization, and seed maturation, ultimately reducing fruit yield. High temperatures during flowering can stimulate auxin production, thereby promoting the development of parthenocarpic fruit. Similarly, prolonged darkness or specific light conditions can induce hormonal changes that trigger fruit formation without fertilization. Adequate water supply is essential for fruit growth, as water stress can inhibit parthenocarpy (Dhatt & Kaur 2016; Chaudhari et al. 2024; Ganvit et al. 2024).

In tomatoes, transgenic plants with RNA interference (RNAi) of the *Solanum lycopersicum TOPLESS 1* (*SlTPL1*) gene produced fruit with normal seeds under standard conditions without pleiotropic effects. However, these plants developed seedless fruits when emasculated or exposed to heat stress, demonstrating the interaction between genetic regulation and environmental signals in the induction of parthenocarpy (He et al. 2021).

Pollination and fertilization

Although parthenocarpy refers to fruit development without fertilization, pollination and fertilization can still influence its occurrence. In some cases, pollination triggers hormonal signals that promote fruit formation, while fertilization can further enhance the growth and quality of parthenocarpic fruits. When pollinators such as bees or other insects are scarce or absent, plants can develop fruit without fertilization, thus ensuring continued fruit production despite inefficient pollination. The interaction between pollination, fertilization, and parthenocarpy is complex and varies among plant species (Chaudhari et al. 2024; Ganvit et al. 2024).

INDUCTION OF PARTHENOCARPY AND ITS EFFECTS ON CROP QUALITY

Tomato (*Solanum lycopersicum* L.)

To obtain parthenocarpic transgenic tomato plants without inducing undesirable phenotypes, two genes, *Solyc03g007780* and *Solyc02g067760*, were identified as being distinctly expressed in ovary tissues but not in vegetative parts. *Solyc03g007780* is expressed in developing ovaries and anthers, whereas *Solyc02g067760* mRNA is present throughout the flower tissue. The promoters of these

genes – Psol80 for *Solyc03g007780* and Psol60 for *Solyc02g067760* – drive expression predominantly in specific floral tissues: Psol80 directs gene expression in the ovule, placenta, endocarp, and pollen, while Psol60 promotes expression throughout the flower. Although the weight of parthenocarpic fruits in the Psol80/60-*Solanum lycopersicum Indole-3-Acetic Acid 9 inhibition* (*SlIAA9i*) lines was lower than those pollinated in the wild type, the results were nevertheless promising (Kim et al. 2019).

Natural parthenocarpic tomato genotypes exhibit higher yield percentages than normal seeded varieties. However, the fruits of natural parthenocarpic tomato are smaller in both weight and size than those with normal seeds. Morphologically, natural parthenocarpic tomato fruits are typically round, whereas those with normal seeds tend to be elongated (Dominic et al. 2021). Three well-known sources of facultative parthenocarpy in tomato are Soressi (Montfavet-191), Severianin, and RP75/59 (Chaudhari et al. 2024). The introduction of the mutation allele 3 (iaa9-3) of the *Indole-3-Acetic Acid 9* (*IAA9*) gene into tomato cultivars resulted in the development of parthenocarpic lines that produce seedless fruit of better quality than seeded fruit. This enhancement is attributed to increased placental mass and higher total soluble solids (TSS) levels compared to locular tissue (Chaudhari et al. 2024).

Additionally, a mutation in the *SlAGL6* gene has been identified as the cause of the parthenocarpic phenotype. Plants carrying this mutation can produce fruit even under heat stress conditions that severely impair fertilization-based fruit set. Unlike other recessive monogenic tomato mutants that induce parthenocarpy, *SlAGL6* mutations do not cause homeotic alterations. The resulting seedless fruits maintain normal weight and shape, pollen viability is unaffected, and plants retain the ability to reproduce sexually. These characteristics make *SlAGL6* a promising candidate gene for inducing facultative parthenocarpy in tomato (Klap et al. 2017).

To induce parthenocarpy in tomatoes, polyploid cultivars, particularly triploid tomatoes, can be developed. These lines are characterized by higher levels of dry matter and TSS (Fayaz et al. 2021). Elevated concentrations of gibberellins and auxins in the ovary are strongly associated with genetic parthenocarpy in tomato, facilitating fruit development in the absence of fertilization. Compared to seeded cultivars, parthenocarpic tomatoes typically exhibit superior quality traits, including increased sweetness, higher dry matter, higher sugar content, reduced acidity, and increased TSS (Baddigam et al. 2024). Seedless tomatoes are often more flavorful, contain up to 1% more dry matter, higher sugar concentration, lower acidity and cellulose content, and higher TSS. Notably, fruit size, shape, and locule jelly content of seedless tomatoes remain comparable to their seeded counterparts (Ganvit et al. 2024).

Application of cytokinins (CPPU at 100 ppm) and gibberellic acids (GA_3 at 200 ppm) at the anthesis stage effectively induced parthenocarpic fruit formation. Although the weight of fruits induced solely by GA_3 or CPPU was lower than that of pollination-induced fruits, combined application of GA_3 + CPPU to unpollinated flowers resulted in fruit weights comparable to those obtained by pollination, as confirmed by LSD analysis (Fig. 1). Moreover, the pericarp thickness of CPPU-induced fruits was similar to that of GA_3-induced fruits (Ding et al. 2013).

Emasculated tomato ovaries were treated with 70 ppm of GA_3, applied three times at 1-day intervals from 3 to 1 days before anthesis. This treatment induced the development of seedless fruits from unpollinated ovaries. However, these parthenocarpic fruits showed significantly reduced width and length compared to self-pollinated fruits, while fruit shape index remained unaffected. This indicates that GA_3 can stimulate parthenocarpic fruit development in tomato, but the resulting fruits are smaller with no change in overall shape (Niu et al. 2024).

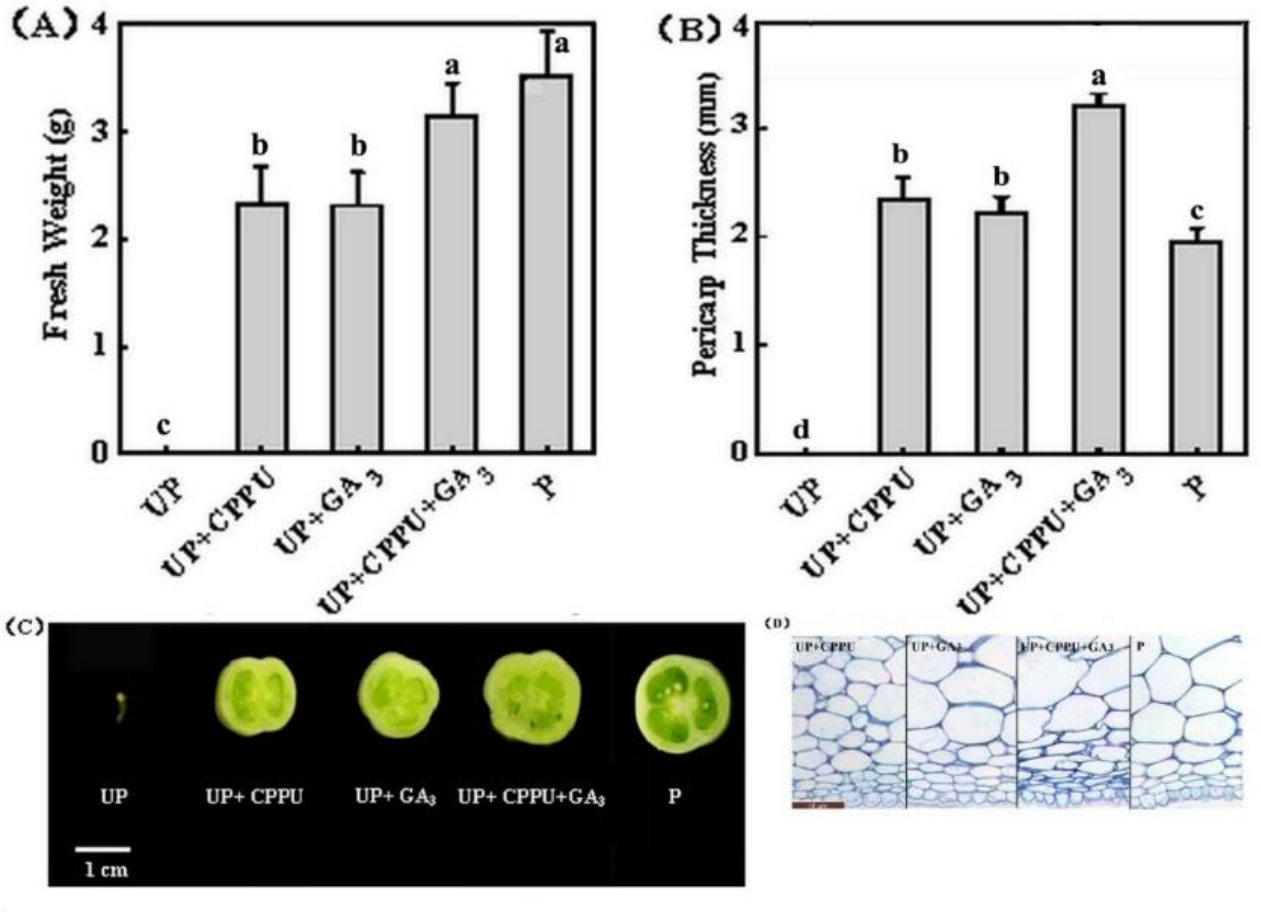

Figure 1. Effects of pollination absence (UP), N-(2-chloro-4-pyridyl)-N′-phenylurea (CPPU), gibberellic acid (GA_3), and pollination (P) on fresh fruit weight (A), pericarp thickness (B), parthenocarpic fruit set (C), and on and pericarp structural thickness (D)
Source: Ding et al. 2013

Eggplant (*Solanum melongena* L.)

Two early parthenocarpic cultivars, 93213-PC-2-1 and 93213-PC-2-3, performed best under net house conditions, showing the highest number of flowers per cluster, fruits per cluster, and marketable fruit per plant. The highest yield per plant was achieved by the hybrid parthenocarpic F_1 cultivar 'Anominori 2 go', obtained from a cross between two parthenocarpic inbred lines (AE-P01 and AE-P24) and 'Anominori', derived from AE-P08 and AE-P01, obtained through pedigree breeding (Chaudhari et al. 2024).

Exogenous application of GA_3 (0.1%, 0.2%, or 0.3%) significantly induced parthenocarpic fruit formation, although the resulting fruits were smaller in weight, length, and diameter compared to the control (Zain & Lapanjang 2015). Under extreme temperature conditions, pollen production and viability are impaired, requiring external support for fruit set. In eggplant, the use of β-naphthoxyacetic acid effectively induced the development of seedless fruits, comparable in size and appearance to pollinated fruits (Makrogianni et al. 2018). Moreover, spraying eggplants during the open flower stage with GA_3 at 2700 ppm or 2,4-D at 2.5 ppm was found to effectively induce parthenocarpic fruit development (Chaudhari et al. 2024).

The parthenocarpic trait in eggplant was also incorporated into desirable cultivars through crossing with high-yielding lines with good fruit quality (Patel et al. 2022; Ganvit et al. 2024). Seedless fruit is highly valued for its superior flesh quality and ease of processing. Furthermore, the development of parthenocarpic eggplants ensures stable fruit production under protected cultivation, even in environments unfavorable to pollinators (Baddigam et al. 2024).

Sweet pepper (*Capsicum annum* L.)

Application of 20 ppm of 2,4-D to the ovaries of 'Shishito' sweet pepper flowers – after removal of the stamens and stigmas – successfully induced parthenocarpic fruit development (Kondo et al. 2021). Similarly, application of 0.05% NAA before anthesis was effective in inducing parthenocarpy in sweet pepper (Fayaz et al. 2021).

In a comparative study, parthenocarpic fruits of the CNPH2622 and 'Shishito' cultivars developed normally but were smaller than those from natural pollination. This indicates that although these cultivars have a high fruit set ability, their capacity for fruit enlargement is limited. Moreover, the length of parthenocarpic fruits consistently remained shorter than that of seeded fruits (Honda et al. 2012; Kondo et al. 2021).

Watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai)

Three main methods are commonly used to produce seedless cultivars (Wijesinghe et al. 2020).

1. Maintaining polyploidy – crossing tetraploid female parents with diploid male parents.
2. Using plant growth regulators – applying cytokinins, for example, to pistillate (female) flowers.
3. Pollination with sterile pollen – pistillate flowers can be pollinated with sterile pollen grains from seeded cultivars that have been irradiated with X-rays or gamma rays.

Seedless watermelon production was recently achieved in Japan by pollinating female seeded watermelon plants with pollen from the intergeneric species bottle gourd (*Lagenaria siceraria* (Molina) Standl.) (Wijesinghe et al. 2020). When bottle gourd pollen was applied to watermelon pistillate flowers, a fruit set rate of 57.1% was recorded, compared to 65.0% with watermelon pollen. Although the set rate with bottle gourd pollen was slightly lower, it exceeded expectations. However, the resulting parthenocarpic fruits were deformed, triangular, or oblong, with a significant difference in fruit length-to-width ratio (Sugiyama et al. 2014). The 'Valentino' hybrid watermelon had a higher overall average fruit weight compared to the other hybrids. It also showed the highest average values for longitudinal and transverse diameters, as well as for the fruit shape index (Oliveira et al. 2020).

Application of 20 ppm CPPU along with pollination with 800 Gy soft-X–irradiated pollen resulted in seedless fruit production in 'Hitorijime-BonBon'. The treated fruit contained no mature seeds, although no significant differences in fruit size or TSS content were observed compared to untreated watermelons (Kawamura et al. 2018). Similarly, application of 500 ppm CPPU during anthesis resulted in completely seedless fruit (Fayaz et al. 2021). Further studies indicated that 200 ppm CPPU combined with 150 ppm NAA significantly induced parthenocarpy in watermelon, with the highest fruit numbers and yield per plant recorded with this treatment (Sravani et al. 2018). Additionally, spraying flowers with 25 ppm 2,4-D resulted in the lowest number of seeds per fruit (Chaudhari et al. 2024).

In terms of fruit quality, TSS values were found to be higher in autotetraploid fruits than in autotriploid fruits, which in turn had higher TSS than diploid fruits (Davis et al. 2013). All parthenocarpic fruits produced by pollination with bottle gourd (*Lagenaria siceraria*) pollen exhibited fruit weight, rind thickness, flesh color, and Brix values comparable to control fruits (Sugiyama et al. 2014). Triploid cultivars exhibited greater firmness but lower sugar content than diploid cultivars, making them more susceptible to postharvest declines in sensory quality due to sugar depletion (Kyriacou et al. 2020). However, the shape, flavor, and yield of seedless watermelon cultivars were comparable to seeded cultivars, and seedless types generally showed a longer shelf life. Importantly, no significant differences in sugar content were observed between seeded and seedless watermelons (Ganvit et al. 2024).

Muskmelon (*Cucumis melo* L.)

Pollen irradiated with 550 Gy of gamma rays resulted in 100% parthenocarpic fruit formation in muskmelon (Bagheri et al. 2021). Application of 10 ppm CPPU during anthesis in muskmelon also induced 100% parthenocarpic fruit set (Fayaz et al. 2021).

Cucumber (*Cucumis sativus* L.)

Exogenous application of phytohormones before flower opening, when the flowers were covered to prevent natural pollination, had a pronounced effect on inducing parthenocarpic fruit development in the nonparthenocarpic cucumber genotype IMPU-1. The highest parthenocarpic fruit set (89.3%) was achieved with the combined application of 100 ppm IAA and 100 ppm of zeatin. Parthenocarpic fruit set was comparable to that observed in naturally parthenocarpic genotypes PPC-6 and DG-8 (Mandal et al. 2022).

Additionally, application of CPPU, NAA, or 100 ppm GA_{4+7} to female flowers the day before and during anthesis successfully induced parthenocarpic fruit formation. The fruits resulting from these treatments had a weight, size, and shape similar to those of pollinated fruits. NAA treatment did not affect the appearance or nutritional quality at harvest or during storage. In contrast, CPPU increased flesh firmness at harvest but decreased phenolic acid and vitamin C content after storage. GA_{4+7} treatment decreased flesh firmness but increased total flavonoid and protein content during storage (Qian et al. 2018). Moreover, application of 100 ppm GA_3 during the pre-anthesis stage effectively induced parthenocarpic fruit development (Chaudhari et al. 2024).

Exogenous application of sugars, particularly fructose and sucrose, also significantly promoted parthenocarpic fruit set and growth. Transcriptome analysis revealed stronger expression of auxin- and cytokinin-responsive genes in sugar-treated fruits. Specifically, the *Indole-3-acetic acid-inducible* gene (*IAA14*) (auxin-responsive) and cytokinin-responsive genes encoding histidine-containing phosphotransfer protein 4 and two-component response regulator 17 were upregulated in sugar-induced parthenocarpic fruits. These results indicate that interactions between sugar and hormones regulate parthenocarpic fruit formation in cucumber (Wang et al. 2021).

Further studies demonstrated that the F_2 hybrid PPC-2 × Pusa Uday produced a substantial number of parthenocarpic fruits both early and late in the season (Jat et al. 2017). Hybrids combining parthenocarpy and gynoecy have revolutionized greenhouse cucumber cultivation, enabling year-round high yields and superior fruit quality. These hybrids are advantageous in terms of consumer preference, yield potential, earliness, and reduced dependence on pollination (Baddigam et al. 2024).

Moreover, 100 ppm CPPU, applied to flowers pinched the day before and on the day of anthesis, induced parthenocarpic fruit set in unpollinated ovaries by upregulating cytokinin-signaling genes. CPPU treatment did not alter fruit shape, texture, or major nutrients such as protein, total flavonoids, and vitamin C, but reduced phenolic acid content. However, the total sugar content of parthenocarpic fruits was significantly lower than that of pollinated fruits, which negatively affected their sweetness (Su et al. 2021; Ganvit et al. 2024).

Pointed gourd (*Trichosanthes dioica*)

Crossing tetraploid maternal plants with compatible diploid paternal plants (4x × 2x) resulted in fruit set rates and fruit shape comparable to diploid plants. Importantly, the number of seeds per fruit was drastically reduced, reaching an average of 1.8 compared to 26.4 in naturally pollinated diploid fruits. These findings indicate that colchicine-induced tetraploid females are a valuable genetic sources for producing fruit with fewer seeds. Furthermore, the genetic stability of tetraploid clones can be effectively maintained through vine cuttings, making them suitable for further breeding and cultivation (Hassan et al. 2020).

Cucurbits (*Cucurbita*)

The highest percentage of haploid plants (23.8–25.3%) in Styrian pumpkin (*C. pepo* var. *styriaca*) was achieved by irradiating pollen grains with 100 Gy of gamma rays, saving embryos in the globular and torpedo stages of development (Ebrahimzadeh et al. 2021). Additionally, foliar application of 150 ppm GA_3 resulted in parthenocarpic fruit set in 96.9% of the tested plants (Fayaz et al. 2021).

Parthenocarpic cultivars of summer squash, particularly the zucchini type (*C. pepo*), were developed to enable fruit production without the need for pollination. These cultivars offer significant advantages in fruit quality and yield, particularly when grown under row covers, which prevent natural pollination (Baddigam et al. 2024).

'Miyazaki-wase No. 1' is a naturally parthenocarpic cultivar. However, fruit set was lower than that of pollinated fruit. No significant differences in fruit quality were observed compared to pollinated fruit (Takisawa et al. 2021). Furthermore, application of NAA, GA_3, CPPU, and brassinolide to female flowers before anthesis successfully induced parthenocarpy in tropical squash (*C. moschata* 'Kogiku'). The effect of hormone-induced parthenocarpy on fruit quality varied depending on the type of phytohormone applied (Ogawa & Takisawa 2022).

Okra (*Abelmoschus esculentus* L.)

The technique of injecting 100 ppm and 200 ppm of IAA into the flower buds and ovary, an innovative approach, was effective in producing seedless okra. Treatment with 100 ppm IAA resulted in increased pod length, diameter, weight, size, TSS, vitamin C, chlorophyll, and photosynthetic efficiency (Fv/Fm) (Hossain et al. 2021). Furthermore, injection of 100 ppm IAA into the ovaries during anthesis enabled 100% pod set and produced seedless okra with improved quality parameters (Sharif et al. 2022).

CONCLUSION

Parthenocarpy in fruit vegetables leads to the production of seedless fruits and pods, enhances fruit set, and contributes to higher yields and improved fruit quality, including increased TSS and longer shelf life. Parthenocarpic fruits often exhibit uniformity, slightly smaller size and weight, while producing a greater number of fruits per plant. In some fruit vegetable species, parthenocarpy also affects fruit shape, flavor, and β-carotene metabolism during storage.

Author contribution statement

M Amin – A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article

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Conflict of interest

The authors confirm that there are no conflicts of interest in any aspect of this paper.

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