

DEVELOPMENT OF BREEDING TECHNIQUES AND SEED PRODUCTION TESTING FOR PARTHENOCARPCIC CUCUMBER VARIETIES IN PLANT FACTORY WITH ARTIFICIAL LIGHTING SYSTEM

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Received: September 30, 2024; Revised: July 30, 2025; Accepted: September 25, 2025

Abstract

This study investigated the refinement of breeding techniques and the selection of parthenocarpic cucumber varieties within a Plant Factory with Artificial Lighting (PFAL) system. We addressed the challenge of inducing male flower production in parthenocarpic cucumbers, which typically do not require male flowers for fruit production, by testing silver nitrate at concentrations of 0, 100, 200, 300, and 500 ppm. Silver nitrate successfully induced male flowers at concentrations of 300 and 500 ppm, with 300 ppm being optimal due to phytotoxicity observed at 500 ppm, which impaired plant growth. Subsequently, we optimized seed production by cultivating cucumber varieties 'Smile' and 'Basha' under controlled lighting conditions using a combination of white and white+red+blue light at an intensity of 300–500 $\mu\text{mol m}^{-2}\text{s}^{-1}$ for 16 hours per day in the PFAL system. The seed production cycle was streamlined to 70 days, with plants reaching pollination readiness at 23 days and completing seed development within 45 days. Lighting conditions and cucumber varieties did not significantly affect seed characteristics such as number, weight, or germination rates. In summary, our research demonstrated that using 300 ppm silver nitrate and managing controlled lighting conditions can effectively enhance breeding and seed production processes for parthenocarpic cucumbers, offering valuable insights to improve the efficiency and reduce the duration of cucumber breeding programs in Thailand.

Keywords: Cucumis sativus; Parthenocarpy; Cucumber breeding techniques; Plant factory with artificial lighting (PFAL); Controlled environment agriculture; Phytotoxicity; Silver nitrate

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Introduction

Cucumbers (*Cucumis sativus* L.) are a major fruit vegetable globally, valued for their consumption both fresh and processed, and find applications in the cosmetics and pharmaceutical industries. In Thailand, the favorable climate supports year-round cultivation of cucumbers, which has historically been a significant agricultural activity. However, recent statistics reveal a notable decline in cucumber cultivation area from 117,125 rai in 2017 to just 37,265 rai in 2020, highlighting challenges in maintaining production levels (Department of Agricultural Extension, 2020). Despite this decline, cucumbers remain economically significant, particularly due to their role in industrial use and export, with cucumber seeds being a prominent export product. Thailand ranks third in the Southeast Asian and South Asian seed markets, following India and Indonesia. A key innovation in cucumber breeding is the development of parthenocarpic varieties, which produce fruit without the need for pollination. These varieties, such as the Beit Alpha, command higher prices—approximately 3-7 times more than regular cucumber seeds—due to their advantageous traits of extending shelf life and ensuring stable fruit setting. The market for parthenocarpic cucumber seeds is dominated by hybrid varieties, which, while offering high productivity, necessitate the purchase of new seeds each season, as they cannot be reused (Chen and Zhou, 2011; Singathiya *et al.*, 2025).

The cultivation of parthenocarpic cucumbers presents unique challenges. Factors such as temperature, light duration, and pest problems can affect fruit production and seed quality. Pollination by insects, common in open-field cultivation, can lead to seed development and reduced fruit setting. Pests, particularly from sucking insects and fruit flies, exacerbate these issues due to the cucumbers' smooth skin and watery flesh. To address these challenges, controlled environment agriculture (CEA) methods, such as Plant Factories with Artificial Light system (PFAL), have been developed. These systems simulate optimal conditions, enhancing seed production efficiency and improving breeding outcomes. An essential component of PFAL systems is the provision of appropriate lighting conditions. Light quality, intensity, and duration are crucial for optimizing plant growth and fruit production. In PFAL systems, the use of LED lights with a tailored spectrum, including a combination of red and blue wavelengths, has been shown to improve plant growth and yield. Red light (620-700 nm) promotes fruiting and overall growth, while blue light (400-

500 nm) supports leaf development and stem elongation (Morrow, 2008; Li *et al.*, 2014). Adjusting light intensity and photoperiod according to the specific needs of the crops can significantly enhance productivity and quality. For instance, cucumbers typically benefit from high light intensity and a photoperiod of 12-16 hours per day, which can be effectively managed in a PFAL environment (Kozai *et al.*, 2015; An *et al.*, 2021).

The increasing demand for high-quality food production, coupled with the challenges of traditional agriculture, has led to significant advancements in CEA. Among these innovations, PFAL offers a promising solution by enabling precise control over environmental conditions such as light quality, intensity, and photoperiod (Kozai *et al.*, 2015; An *et al.*, 2021). Such precision is crucial for optimizing plant growth, enhancing production efficiency, and accelerating breeding cycles, particularly for specialty crops like parthenocarpic cucumbers. PFAL systems, which allow for fruit formation without fertilization, are highly valued for their seedless nature and uniform production, making them ideal for refining cultivation and improving breeding programs. A key challenge in breeding gynoecious cucumber lines, which predominantly produce female flowers, is the absence or rarity of male flowers. This limitation hinders hybrid seed production and complicates the development of stable lines. To overcome this, synthetic hormones such as gibberellins and silver-based compounds, notably silver nitrate (AgNO_3), have been widely used to alter sex expression and induce staminate (male) flower formation (Behera *et al.*, 2010; Yamasaki and Manabe, 2011). AgNO_3 is particularly effective due to its role in inhibiting ethylene, a hormone responsible for promoting female flower development (Beyer, 1976; Nijs and Visser, 1979; Hoque *et al.*, 2002; Behera *et al.*, 2010).

However, the success of male flower induction depends on several factors, including the concentration of AgNO_3 , the application method, and the developmental stage at the time of treatment (Kasrawi, 1988). Although AgNO_3 is effective, studies have reported phytotoxic effects at high concentrations, including leaf curling, brown leaf spots, stem cracking, and inhibited plant growth (Hirayama and Alonso, 2000; Law *et al.*, 2002; Stankovic and Prodanovic, 2002; Hallidri, 2004; Golabadi *et al.*, 2015; Meena, 2015). Mishra *et al.* (2022) further confirmed that concentrations above 800 ppm result in severe phytotoxicity, while lower concentrations are often insufficient for male flower

induction. As such, determining the optimal concentration and application timing of AgNO_3 remains a critical gap in parthenocarpic cucumber breeding, particularly under controlled environment conditions. To address this, the present study investigates strategies for effective staminate flower induction in parthenocarpic cucumbers grown within PFAL systems. Special emphasis is placed on fine-tuning silver nitrate concentrations and application protocols under artificial lighting. By combining hormonal treatments with precise environmental control, this research seeks to enhance seed production efficiency and improve breeding reliability. The findings are expected to contribute to the development of elite parthenocarpic cucumber cultivars and support the advancement of sustainable indoor agricultural systems in tropical and subtropical regions, including Thailand.

Materials and Methods

Treatment Conditions for Sex Expression Modulation to Induce Male Flowers in Gynoecious Lines:

Four parthenocarpic cucumber varieties were used in this study: Smile, Basha, Aaima, and Bayo. These varieties were chosen due to their gynoecious nature, which produces only female flowers. To induce male flower formation in the female flowers for fertilization, a AgNO_3 solution was applied. In the AgNO_3 treatments, when the plants had developed two true leaves, the shoot apices were sprayed with the solution every seven days for four weeks. The spraying was conducted at 5:00 p.m., ensuring full coverage of the leaves, following the method described by Mishra *et al.* (2022). The experiment was carried out in two environments: a PFAL system and a greenhouse, with varying concentrations of AgNO_3 applied, as listed in Table 1.

Plants were grown in February 2023 at the SUT Farm, Suranaree University of Technology. The experiment included two conditions. Firstly, the PFAL system, which used W-FL (White fluorescent Light) + RB-LED (Red and Blue Light

Light Emitting Diode) lighting with a light intensity of $300 \mu\text{mol m}^{-2}\text{s}^{-1}$, controlled the temperature at 27°C , and maintained a photoperiod of 16 hours per day. Detailed light spectra are provided in Figure 1. Two concentrations of silver nitrate were tested: 0 ppm and 500 ppm. Secondly, the greenhouse conditions (a light intensity of $1,100 \mu\text{mol m}^{-2}\text{s}^{-1}$) experiment tested four concentrations of silver nitrate: 100 ppm, 200 ppm, 300 ppm, and 500 ppm. The experimental design was a completely randomized design (CRD) with three replications per treatment. The growing medium comprised coconut coir, sand, and rice husk at a 2:1:1 (v/v) ratio, supplemented with chopped coconut husk at a 1:1 (v/v) ratio. A drip irrigation system was employed, delivering 0.5 L/plant/day before fruit set and 1.0 L/plant/day after fruit set. Basal fertilizer (16-16-16) was applied at 5 g/plant prior to transplanting. After transplanting, a combination of 16-16-16 and 46-0-0 was applied at 5 g/plant every three days for four applications. During the harvesting period, 16-16-16 and 13-13-21 were applied at the same rate and interval for thirteen applications. Calcium and boron were applied weekly as foliar micronutrient supplements. The sex expression of each plant was evaluated based on the percentage of different flower phenotypes, the node at which the first female/bisexual flower appeared, and the number of female/bisexual flowers per plant within the first 30 nodes of the main shoots. The effects of treatment with different concentrations of silver nitrate on the sex expression of all parthenocarpic cucumbers were assessed. Statistical analysis was performed using ANOVA followed by Duncan's multiple range test, using SPSS 16.0.

Evaluating Pollination and Fruit Set for Hybrid Seed Production of Parthenocarpic Cucumbers in PFAL Systems:

Silver nitrate was used to maintain gynoecious characteristics. After developing breeding techniques and selecting parthenocarpic cucumber varieties in PFAL systems, we tested hybrid seed production of these cucumbers.

Table 1. Concentrations of silver nitrate solution tested in the PFAL and greenhouse conditions

Environments	Varieties	Concentration of AgNO_3	Environments	Varieties	Concentration of AgNO_3
PFAL	Basha	0 ppm	Greenhouse	Basha	100 ppm
	Smile	500 ppm		Smile	200 ppm
				Aaima	300 ppm
				Bayo	500 ppm

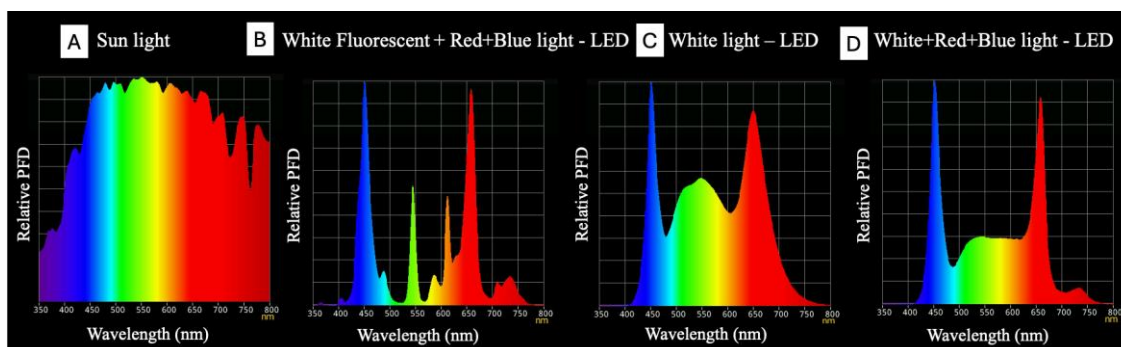


Figure 1. Spectral characteristics of sunlight (A), white fluorescent + red + blue light LED (B), white light LED (C), and white + red + blue light LED (D) used in the experiment

The cucumber varieties ‘Smile’ and ‘Basha’ were selected for hybrid production and seed testing due to their high yield and compact fruit size. These traits are desirable for snack cucumber development, which was one of the objectives of this study. Two cross combinations were tested: Smile x Basha and Basha x Smile. These were grown under different LED lighting conditions: 1) W-LED and 2) WRB-LED, with a light intensity of $500 \mu\text{mol m}^{-2} \text{s}^{-1}$, a temperature of 27°C , and a photoperiod of 16 hours per day. Detailed light spectra are provided in Figure 1.

Seed Germination Assessment:

Seed germination was evaluated under controlled laboratory conditions using the Between Paper (BP) method. Fifty seeds were randomly selected per treatment with four replications. Seeds were positioned on paper and incubated in a germinator. Optimal conditions were maintained with alternating temperatures (25°C for 16 h and 30°C for 8 h) and 50% relative humidity. Parameters Measured: 1) Root Germination: Radicle emergence was recorded daily from Day 1 to Day 8. Data were expressed as root germination percentage and root germination rate (plants/day). 2) Normal Seedling Germination: Normal seedling counts were conducted daily from Day 4 (first count) to Day 8 (final count), adhering to ISTA (2014) guidelines. Results were reported as germination percentage and germination speed (plants/day), calculated according to AOSA (1983). 3) Speed of germination: This metric assessed the speed of germination, reflecting seed vigor. Daily germinated seedlings were counted, and the index was calculated as: $\text{Speed of germination} = \frac{\sum(\text{Number of germinated seedlings/Days after sowing})}{\text{Total number of seeds}}$. 4) Seedling Growth Rate: Vigor was further quantified by measuring the dry weight of normal seedlings. Shoot and root dry weights were recorded, and the growth rate was calculated as:

$\text{Seedling Growth Rate} = \frac{\text{Dry weight of shoots and roots/Number of normal seedlings}}{\text{Days after sowing}}$. 5) Seedling Vigor Classification: Seedlings were categorized into high, moderate, and low vigor based on morphological attributes (root system, hypocotyl, cotyledons, and epicotyl). High vigor seedlings were complete and minimally damaged ($\leq 10\%$ cotyledon damage), indicating high potential for field establishment. Moderate vigor seedlings were smaller ($< 50\%$ of the largest) with cotyledon damage up to 25%. Low vigor seedlings were also smaller ($< 50\%$ of the longest) with cotyledon damage approaching 50%, considered unlikely to establish in the field. And 6) Seedling Length: For normal seedlings, shoot and root lengths were measured separately to the nearest 0.1 cm. Total seedling length was determined by summing the average shoot and root lengths.

Results

Effect of AgNO_3 application on sex expression in parthenocarpic cucumber plants:

Figure 2 and Figure 3 show the effects of AgNO_3 on the sex expression of gynoecious cucumber plants (‘Smile’, ‘Basha’, ‘Aaima’, and ‘Bayo’). Control plants (‘Smile’ and ‘Basha’ with 0 ppm AgNO_3) produced only female flowers. When observed up to node 30 on the main stem, 100% of these control plants had female flowers. In contrast, cucumber varieties sprayed with a 500 ppm AgNO_3 solution in the PFAL system exhibited all three flower sex characteristics: male flowers, female flowers, and bisexual flowers. The predominant characteristic was male flowers. The ‘Smile’ variety exhibited 86.64% male flowers, 8.14% female flowers, and 5.22% bisexual flowers. Meanwhile, the ‘Basha’ variety showed 78.95% male flowers, 20% female flowers, and only 1.05% bisexual flowers. Following the application of silver nitrate

and data collection on flower sex expression in the greenhouse, it was observed that spraying silver nitrate resulted in the conversion of flowers in all parthenocarpic cucumber varieties from female to male and bisexual flower types, with varying percentages of flower expression. Among the four tested varieties, a concentration of 500 ppm yielded the highest percentage of male flowers, with 85.77%, 87.20%, 76.51%, and 75% for the Basha, Smile, Aima, and Bayo varieties, respectively. This was followed by the 300 ppm concentration, which produced 70.83%, 76.51%, 71.42%, and 74.14% male flowers in the Basha, Smile, Aima, and Bayo varieties, respectively. Conversely, the 100 ppm and 200 ppm concentrations resulted in the lowest percentages of male flowers, ranging

from 45% to 69%, depending on the variety. Additionally, all concentrations led to the presence of female and bisexual flowers. However, the number of male flowers was lower compared to the number of female flowers, as illustrated in Figure 2. These findings indicate that silver nitrate acts similarly to gibberellin in inducing the formation of male stamens. In subsequent studies, the male stamens obtained from this sex conversion were used for hybridization to develop breeding techniques and select parthenocarpic cucumber varieties in PFAL systems. This involved testing pollination, studying fruit set, and identifying the appropriate harvest index to demonstrate that inducing male flowers by spraying silver nitrate can facilitate the formation of complete male gametes.

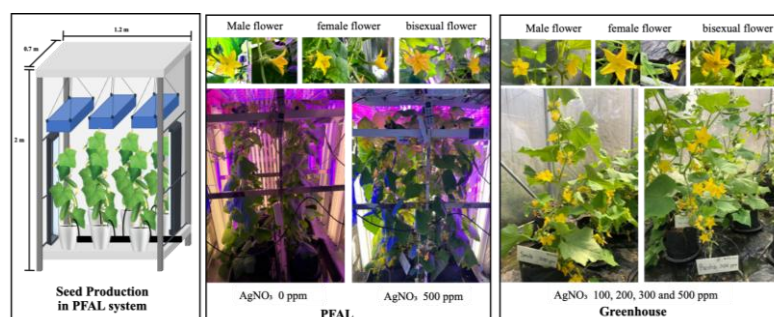


Figure 2. Seed production in PFAL system and flower phenotypes in parthenocarpic cucumbers and morphological changes in response to AgNO₃ concentrations of 100 ppm, 200 ppm, 300 ppm, and 500 ppm.

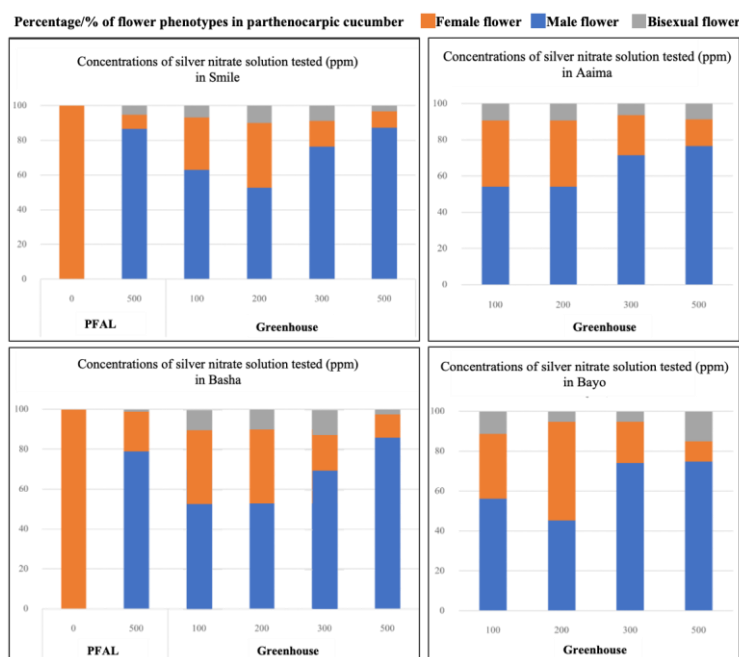


Figure 3. Effects of AgNO₃ on the percentages of male, female, and bisexual flowers in parthenocarpic cucumbers (Basha, Smile, Aima, and Bayo varieties) grown under the PFAL system and in a greenhouse

It was found that the distinct growing environments of the PFAL system and greenhouse did not influence the induction of male flowers in cucumbers. This suggests that breeding programs for cucumber varieties can be effectively conducted within the PFAL system without relying on external environmental factors.

Effect of Pollination and Fruit Set on Hybrid Seed Production of Parthenocarpic Cucumbers in PFAL Systems

Optimal AgNO₃ Concentration for Male Flower Induction: A concentration of 300 ppm AgNO₃ was identified as the most effective for promoting male flower production. Concentrations of 0, 100, and 200 ppm were less effective, whereas 500 ppm caused phytotoxicity. Although 100 ppm AgNO₃ induced male flower formation in parthenocarpic cucumbers (Figure 3), 300 ppm consistently produced a higher number of male flowers than both 100 and 200 ppm. Therefore, 300 ppm AgNO₃ is recommended due to its superior efficacy. This concentration also offers practical advantages by reducing plant requirements, lowering costs, and avoiding the phytotoxic effects observed at 500 ppm. These findings confirm that 300 ppm AgNO₃ is optimal for male flower induction and highly suitable for breeding programs aimed at improving the PFAL system.

From the pollination study aimed at evaluating the production of parthenocarpic cucumber seeds in the PFAL system, it was found that male pollen, which had been sex-transformed with silver nitrate, could be effectively utilized for seed production testing. Specifically, the hybrid Smile x Basha

yielded 24 fruits, while Basha x Smile produced 22 fruits. This indicates that 12 cucumber plants, cultivated in a PFAL system with an area of 1.68 square meters, were capable of producing 46 fruits per crop.

Both lighting conditions appeared to have a similar effect on the number of cucumber fruits capable of producing seeds. However, the Smile x Basha hybrid demonstrated the ability to be pollinated at lower nodes compared to the Basha x Smile hybrid. This suggests that the choice of cucumber varieties influences both the seed production period and harvest. Despite these differences, no statistical significance was observed regarding the day of cross-pollination, fruit development into seeds, number of fruits per plant, number of seeds per fruit, or the weight of 100 seeds. As shown in Table 2.

The rapid production of varieties in the PFAL system should focus on the nodes where pollination occurs, as expedited pollination facilitates quicker seed development. Cucumber plants in the PFAL system produced 46 fruits per crop with high seed quality. The development of breeding techniques and the selection of parthenocarpic cucumber varieties, including the study of flower sex expression, pollination testing, and fruit set, demonstrated that parthenocarpic cucumbers can be sex-changed through silver nitrate spraying. Male flowers derived from sex-changed plants can successfully pollinate and produce seeds, as illustrated in Figure 4. The newly developed cucumber seeds from the PFAL system are suitable for testing their quality and viability for parthenocarpic cucumber seed production.

Table 2. Average days of cross-pollination, fruit and seed development, number of fruits per plant, number of seeds per fruit, and 100-seed weight (g) in parthenocarpic cucumbers for hybrid seeds (Parthenocarpic Cucumbers x Parthenocarpic Cucumbers)

Light/Hybrid	Days of cross-pollinated	Days of fruit and seed development	Number of Fruit per plant	Number of seeds per fruit	100 seed weight (g)
(A) Light					
W	24.19±0.61	45.81±0.61	3.81±0.61	194.57±10.16	2.98±0.16b
WRB	23.65±0.67	46.35±0.67	3.85±0.67	206.15±12.25	3.22±0.11a
(B) Hybrid seeds (Parthenocarpic x Parthenocarpic)					
Basha x Smile	24.19±0.68	45.81±0.68	4.81±0.68	189.06±10.84	3.07±3.76
Smile x Basha	23.65±0.45	46.35±0.45	3.35±0.45	211.66±7.96	3.14±1.87
F-test					
A	ns	ns	ns	ns	*
B	ns	ns	ns	ns	ns
AxB	ns	ns	ns	ns	ns
CV (%)	12.95	6.73	7.73	22.60	21.71

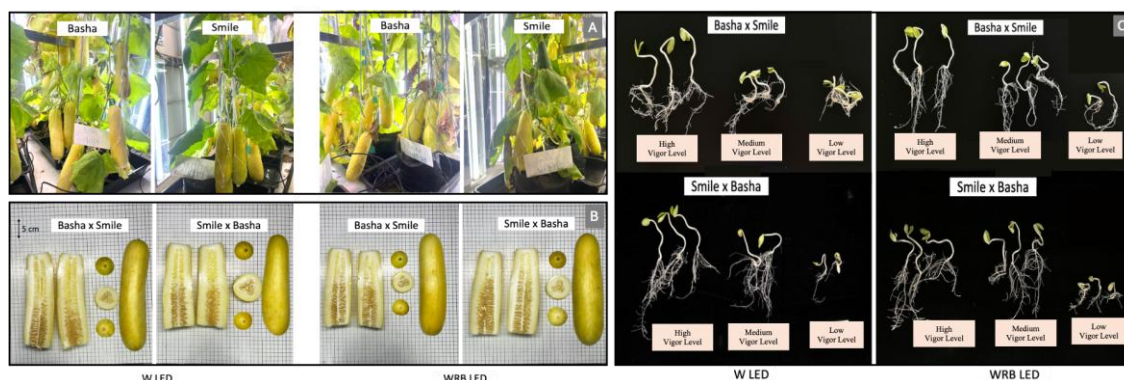


Figure 4. Effect of cross-pollination and light quality on seed germination in parthenocarpic cucumbers at 70 days after sowing

The quality of hybrid seeds produced from parthenocarpic cucumber cultivation in the PFAL system was assessed through germination tests conducted in the laboratory. The evaluation included assessing normal seedlings at two stages: 1) day 4 after sowing (first count) and 2) day 8 after sowing (final count). The results indicated that the germination percentage for both types of light (white light and white-red-blue light) and both cucumber varieties (Smile and Basha) did not differ statistically. This suggests that hybrid seeds can be effectively produced in the PFAL system under both lighting conditions, with a germination percentage exceeding 90%. By day 8, the germination rate of hybrid cucumbers reached 97-99% for both lighting conditions. Regarding seedling vigor, the assessment of seed germination rate, seedling growth rate, and the length of shoots and roots showed no significant effect of lighting or variety on seedling vigor. However, seeds produced under white light exhibited a tendency for higher

germination rates, greater seedling growth rates, and longer shoot and root lengths compared to those produced under white-red-blue light. Additionally, the use of the Smile cucumber variety as the maternal plant tended to result in higher germination rates and longer shoot and root lengths compared to the Basha variety. Conversely, the Basha variety exhibited a higher seedling growth rate compared to seeds from the Smile variety, as shown in Table 3.

The examination of seedling vigor by classifying seedlings into high, medium, and low vigor categories revealed no statistical differences between the lighting conditions or cucumber varieties. Nonetheless, seed production under white light tended to produce stronger seedlings compared to white-red-blue light. Furthermore, the Smile cucumber variety generally produced stronger seedlings than the Basha variety, as illustrated in Table 4.

Table 3. Average days of cross-pollination, fruit and seed development, number of fruits per plant, number of seeds per fruit, and 100-seed weight (g) in parthenocarpic cucumbers for hybrid seeds (Parthenocarpic Cucumbers x Parthenocarpic Cucumbers)

Light/Hybrid	Germination (%)		Speed of Germination	Seedling Length (cm)	
	first count	final count		Stem	Root
(A) Light					
W	95.25±2.03	98.50±0.82	12.31±0.10	6.40±0.17	8.75±0.48
WRB	93.00±4.47	98.00±1.46	12.25±0.18	6.35±0.20	8.55±0.29
(B) Hybrid seeds (Parthenocarpic x Parthenocarpic)					
Basha x Smile	91.75±4.37	97.00±1.51	12.13±0.19	6.28±0.16	8.63±0.43
Smile x Basha	96.50±1.95	99.50±0.33	12.44±0.04	6.47±0.21	8.66±0.37
F-test					
A	ns	ns	ns	ns	ns
B	ns	ns	ns	ns	ns
AxB	ns	ns	ns	ns	ns
CV (%)	10.80	3.38	3.38	8.66	14.04

Table 4. Their mean values of seedling growth rate and vigor indexes for hybrid seeds (Parthenocarpic Cucumbers x Parthenocarpic Cucumbers)

Light/Hybrid	Seedling Growth Rate	Seedling vigor classification (%)		
		High Vigor Level	Medium Vigor Level	Low Vigor Level
(A) Light				
W	5.29±0.32	87.50±4.29	8.00±3.14	2.25±0.88
WRB	5.10±0.26	82.25±9.29	20.75±12.83	5.00±1.93
(B) Hybrid seeds (Parthenocarpic Cucumbers x Parthenocarpic Cucumbers)				
Basha x Smile	5.36±0.21	79.75±9.06	13.00±6.07	4.25±1.67
Smile x Basha	5.04±0.35	90.00±4.14	15.75±12.19	3.00±1.46
F-test				
A	ns	ns	ns	ns
B	ns	ns	ns	ns
AxB	ns	ns	ns	ns
CV (%)	15.86	24.84	196.81	124.65

Discussion and Conclusions

This study demonstrated that 300 ppm AgNO₃ was the optimal concentration for inducing male flower formation in gynoecious parthenocarpic cucumber varieties. Lower concentrations (100 and 200 ppm) were less effective, and higher concentration (500 ppm) resulted in phytotoxicity. These findings are consistent with prior studies reporting that AgNO₃ suppresses ethylene signaling, which in turn promotes the development of male or bisexual flowers in gynoecious lines (Seiji and Manabe, 2011). The differential floral morphology observed between AgNO₃-sprayed and non-sprayed flowers confirms this mechanism and demonstrates the practicality of using silver nitrate as a reliable tool for manipulating floral sex expression. Testing parthenocarpic cucumber seed production in a PFAL system involved adjusting environmental conditions based on previous literature. Parthenocarpy in cucumbers is controlled by the incomplete repressive gene *Pc* (Pike and Peterson, 1969) and other polygenic factors (De and Garretsen, 1976). This study successfully demonstrated the feasibility of seed production for parthenocarpic cucumbers under tropical PFAL conditions using optimized parameters, including a light spectrum composed of white and red-white-blue LEDs, a photosynthetic photon flux density (PPFD) of 300–500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, a 16-hour photoperiod, and a stable temperature of 27°C. Seeds were harvested 70 days after planting, with hand-pollination performed on day 23 and seed development taking approximately 45 days. The production system yielded 3–4 fruits per plant, with consistent seed quality, including germination percentage and seedling vigor, across all treatments and cultivars tested. Additional pollination did not significantly increase fruit or seed yield. These results indicate that the PFAL environment, when well-controlled, can maintain stable reproductive

performance and seed quality in parthenocarpic cucumber production.

Importantly, the application of AgNO₃ in combination with PFAL technologies enabled the reliable production of functional seeds from gynoecious lines that would otherwise not produce male flowers. This not only supports the development of inbred lines and hybrids but also enhances the overall efficiency of breeding programs. By facilitating synchronized flowering and reliable seed set under controlled conditions, the approach shortens the breeding cycle, enabling multiple generations to be completed annually regardless of external seasonal variation. Furthermore, the PFAL system demonstrated significant potential in reducing production time and improving resource-use efficiency, particularly under constraints of land, climate, or biosafety requirements. The ability to produce genetically stable, high-quality seeds in a compact and climate-resilient facility supports scalability and repeatability, both critical factors for commercial seed enterprises and research programs aiming to enhance breeding throughput. The integration of artificial lighting, controlled pollination, and regulated growth conditions presents a promising model for modernizing seed production systems, especially for parthenocarpic or gynoecious lines where traditional field-based breeding may be limited.

In conclusion, the findings of this study demonstrate a viable and scalable approach for the production of high-quality seeds from parthenocarpic cucumber varieties using PFAL systems and silver nitrate-induced male flower formation. This approach not only contributes to the advancement of controlled-environment agriculture but also holds significant value for accelerating breeding cycles, improving breeding efficiency, and

enabling year-round seed production in tropical and subtropical regions.

Acknowledgment

This work was supported by (i) Suranaree University of Technology (SUT), (ii) Thailand Science Research and Innovation (TSRI), and (iii) National Science, Research and Innovation Fund (NSRF)

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