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Sex Phenotype Variation of California Papaya (*Carica papaya* L.) Flowers: Its Relationship with Pollen Quality, Seed Germination, and Fruit Characteristics

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ABSTRACT

This study examined the influence of flower sex phenotype variation on pollen quality, seed germination, and fruit characteristics of California papaya (*Carica papaya* L.) using controlled pollination schemes. A completely randomized design was applied, involving self and cross pollination among male, female, and hermaphroditic flower types. Pollen quality was evaluated through viability and germination tests, seed quality was assessed using physiological parameters, and fruit characteristics were analyzed qualitatively and quantitatively. The results revealed that flower sex phenotype significantly affected pollen performance, seed germination, and fruit traits. Normal and elongate hermaphroditic flowers exhibited the highest pollen viability and germination (≥85%), resulting in seeds with superior germination capacity, higher vigor index, and faster growth rates. Fruits derived from self-pollinated hermaphroditic flowers showed more uniform morphology, thicker flesh, moderate water content, and stable sweetness, meeting preferred market standards. In contrast, several cross-pollination combinations involving pistillate and male flowers produced greater variability in fruit shape, lower seed physiological quality, and reduced germination performance. Notably, certain controlled cross pollination schemes yielded fruits with higher sweetness than self-pollinated hermaphroditic fruits, suggesting a physiological pollen effect beyond genetic factors. These findings demonstrate that reproductive performance and fruit quality in California papaya are strongly influenced by flower sex phenotype and pollination combinations. Proper management of pollination strategies based on flower type can serve as an effective approach to improve seed quality and fruit characteristics without altering cultivar genetics.

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis pengaruh variasi fenotipe sex bunga terhadap kualitas polen, daya berkecambah benih, dan karakteristik buah pepaya California (Carica papaya L.) melalui penyerbukan terkendali. Penelitian disusun dalam rancangan acak lengkap non factorial dengan perlakuan utama berupa kombinasi penyerbukan sendiri dan silang antar bunga jantan, betina, dan hermafrodit. Kualitas polen diamati melalui uji viabilitas dan daya berkecambah, mutu fisiologis benih dianalisis berdasarkan parameter perkecambahan dan vigor, sedangkan karakteristik buah dievaluasi secara kualitatif dan kuantitatif. Hasil penelitian menunjukkan bahwa fenotipe sex bunga berpengaruh nyata terhadap sebagian besar parameter yang diamati. Bunga hermafrodit tipe normal dan elongata memiliki viabilitas serta daya berkecambah polen tertinggi (≥85%) dan menghasilkan benih dengan daya berkecambah tinggi, indeks vigor lebih baik, serta kecepatan tumbuh yang lebih tinggi. Buah hasil penyerbukan sendiri dari bunga hermafrodit menunjukkan bentuk yang lebih seragam, daging buah lebih tebal, kadar air sedang, dan tingkat kemanisan stabil sehingga lebih disukai pasar. Sebaliknya, beberapa kombinasi penyerbukan silang antara bunga jantan dan betina menghasilkan variasi morfologi buah yang lebih besar serta mutu benih yang lebih rendah. Beberapa skema penyerbukan silang menghasilkan buah dengan tingkat kemanisan lebih tinggi dibandingkan penyerbukan sendiri dari bunga hermafrodit. Secara keseluruhan, hasil penelitian menegaskan bahwa pengelolaan penyerbukan berdasarkan tipe bunga merupakan strategi efisien untuk meningkatkan mutu benih dan buah pepaya California tanpa memerlukan perbedaan genetik antar kultivar.

INTRODUCTION

The papaya (*Carica papaya* L.) is well known tropical fruit and is widely available in the market, especially in tropical region. Papaya has high commercial value and available almost year round because it bears fruit continuously rather than seasonally. In addition to being consumed as fruit and vegetables, papaya is also utilized for its latex, which contains the enzyme papain, widely used as a meat tenderizer, pharmaceutical, and textile industries (Syukur, 2018). Generally, papaya fruit has a sweet taste and moderate water content (depending on the level of ripeness), crunchy yet soft fruit, a fairly strong aroma, and a contrasting orange color, making it widely popular among the public (Zhou *et al*., 2021).

In Indonesia, one of the most widely cultivated cultivars is the California (also known as Calina) papaya. California papaya is a native Indonesian papaya obtained through a breeding process carried out by Sriani Sujiprihati which was introduced in 2010. This cultivar has the advantage of thick fruit flesh, a crunchy/not mushy texture, a sweet taste, does not rot easily/long lasting in storage, has a short stem height, and has a faster harvest period compared to other papaya cultivars (IPB, 2023). These advantages make the California papaya widely cultivated by farmers for production purposes. In the production process, papaya farmers certainly face several problems, such as pests and diseases, irrigation in dry areas, and weeds, but these can still be overcome. One of the main problems in papaya cultivation is confusion in the expression/phenotype of sex and flower type in plants (Ávila-Hernández *et al*., 2023).

Papaya is a plant where the quality and shape of the fruit are highly dependent on the type of flower and pollination that occurs (Burns *et al*., 2022), so it is very important to

pay attention to tendency of the type of flowering and the sex factor of papaya plant. Papaya plants cultivated by farmers, especially the California cultivar, are trioecious with three sex factors in the flowers, namely male, female, and hermaphrodite (Chávez-Pesqueira & Núñez-Farfán, 2017). Storey (1958) in his research stated that there are 14 types of papaya flowers ranging from fertile to sterile, some female flowers cannot even produce fruit. Then there are several variations of papaya fruit with different characteristics, depending on the type of flower that pollinates and forms the fruit.

Fruit derived from self-pollination of hermaphrodite flowers is the most preferred type in the market because of its uniform shape, sweet taste, and desirable fruit quality (Ávila-Hernández *et al*., 2023). This makes farmers have to carry out a roguing process at the start of planting/transplanting just to ensure that only the papaya plant population with a tendency towards hermaphrodite flowers is cultivated for fruit production. This process is certainly not efficient when viewed from an economic, labor and time perspective.

When viewed from the pollination aspect, the existence of various types of papaya flowers that appear, is also thought to affect the quality of pollen, this is predicted by the success level of pollination in several male flowers to female flowers. Papaya plants that are pollinated intentionally using hands produce better fruit and a higher level of pollination success than naturally/free pollination, this is sufficient to prove that there are several types of male flowers with different pollen quality (Junthasri & Suwanseree, 2022). Whereas pollen quality really determines the success of pollination and also indirectly the genetic diversity that can be created (Nyadanu *et al*., 2023).

California papaya is propagated generatively through seeds, which opens the possibility of genetic and phenotypic variation if the seeds originate from cross pollination. This variation may lead to the loss of desirable traits or the emergence of undesirable ones (Dung *et al*., 2021), therefore farmers tend to use seeds from hermaphrodite fruit. However, the use of hermaphrodite fruit as a large scale seed source will create a conflict with market demand, the majority of which wants hermaphrodite fruit. However, the use of hermaphrodite fruit as a large-scale seed source will create a conflict with market demand, which mostly wants hermaphrodite fruit. Usually, papaya is harvested before physiological maturity for consumption purposes, with the hope that it will be ripe when it reaches consumers. Harvesting fruit before physiological maturity can reduce seed viability and germination (Junior *et al*., 2019).

Understanding this relationship is crucial not only for improving the efficiency of papaya breeding and seed production systems but also for maintaining the uniformity and stability of superior cultivars such as California papaya. Given the increasing market demand for high quality and uniform fruits, as well as the limited availability of reliable seed sources, research on the physiological and reproductive mechanisms underlying sex phenotype variation becomes highly urgent. Furthermore, this study introduces an integrative approach by linking

flower sex phenotype variation with pollen quality, seed germination performance, and fruit characteristics within a single cultivar framework. Such an approach has rarely been applied specifically to the California papaya cultivar, making this research both timely and novel**.** Therefore, this study aims to analyze the relationship between flower sex phenotype variation and its effects on pollen quality, seed germination, and fruit characteristics in California papaya (*Carica papaya* L.) through controlled cross pollination schemes among several flower types.

METHOD

The research was carried out in two locations: a California papaya cultivation site owned by local farmers in Ngargogondo Village, Borobudur District, Magelang Regency and the Plant Physiology Laboratory. The study took place from June 28, 2025 to October 28, 2025. In summary, the research consisted of several sequential stages, including land and flower surveys, determination of pollination schemes, pollen collection (followed by observations of pollen viability and germination), flower emasculation and pollination, plant maintenance, fruit harvesting, fruit characterization, seed extraction, and germination testing.

The equipment used in this study included daggers, scissors, rulers, magnifying glasses, bent splinter tweezers, fine brushes, vortex mixers, oven, fruit moisture meter, object glass, pipettes, 90 mm plastic Petri dishes, water sprayers, compound microscopes, optilab devices, macro lens cameras, counters, and refractometers. The materials used were 15 cm cable ties, plastic name tag labels, filter paper, pollen from male flowers, papaya fruits, 5 ml tubes, labels, Tween solution, tetrazolium solution, Brewbaker and Kwack medium (containing sucrose, $Ca(NO_3)_2 \cdot 2H_2O$, $MgSO_4 \cdot 2H_2O$, H_3BO_3, and KNO_3), NaOCl and distilled water (H_2O).

This experimental study was conducted to design and perform controlled cross and self pollination schemes among different floral sex phenotypes of papaya, in order to elucidate the effects of floral sex variation on pollen quality, seed germination, and fruit characteristics. The planned pollination scheme for California papaya flowers is presented below.

Table 1. Pollination Scheme of Various Flower Types

Scheme	Code	Flower Pollination
1.	Psto x Pstl	♂ Pistillode >< ♀ Pistillate (cross pollination)
2.	Stmt x Pstl	♂ Staminate >< ♀ Pistillate (cross pollination)
3.	Hm (self)	Normal hermaphrodite flower (self pollination)
4.	Hm el (self)	Elongata hermaphrodite flower (self pollination)
5.	Hm pt (self)	Petandria hermaphrodite flower (self pollination)
6.	Hm (n) x Pstl	♂ Hermaphrodite >< ♀ Pistillate (cross pollination)
7.	Psto x Pstl (gr)	♂ Pistillode >< ♀ Pistillate with grooved ovaries (cross pollination)
8.	Pol Hm (gn)	Polygamous hermaphrodite flower (geinotogamy)
9.	Pol Psto x Pstl (gn)	♂ Pistillode >< ♀ Pistillate in polygamous (geinotogamy)
10.	Pol Hm x Pstl (gn)	♂ Hermaphrodite >< ♀ Pistillate in polygamous (geinotogamy)

Scheme	Code	Flower Pollination
11.	Psto x Pstl (abn)	♂ Pistillode >< ♀ Abnormal Pistillate (cross pollination)
12.	Stmt x Hm	♂ Staminate >< ♀ Hermaphrodite (cross pollination)

To assess pollen viability (PV/%) and germination capacity (GC/%), pollen samples were collected from all flower types exhibiting male sex characteristics. The collection was conducted in the morning, from flowers that had reached the anthesis stage. Pollen viability was evaluated using tetrazolium, while pollen germination was tested on Brewbaker and Kwack medium. Both parameters were expressed as percentages (%), with each test performed in six replications.

Germination tests of papaya seeds were conducted in a controlled room using filter paper as the germination medium. Prior to sowing, the seeds were selected for uniform size and then surface-sterilized in a 1% sodium hypochlorite (NaOCl) solution for 5 minutes, followed by rinsing with sterile distilled water and air drying. The seeds were germinated using the rolled paper in plastic method, which involved placing three layers of moist filter paper on a plastic base, evenly arranging the seeds on top, covering them with three additional layers of moist paper, rolling the assembly, labeling it, and placing it in a well ventilated, illuminated room maintained at approximately 27–28°C with a relative humidity of 90–95%.

Observations were conducted daily for 14 days to record the number of normal seedlings. A seedling was classified as normal if it exhibited complete structures, including primary and secondary roots, hypocotyl, cotyledons, epicotyl, and plumule, with a total length at least twice that of the seed. The parameters evaluated included the number of normal (NG), abnormal (AG), and dead seeds (DS), maximum germination capacity (MGC/%), germination rate (GR/%), dry weight of normal seedlings (DWNS/g), vigor index (VI/%), growth uniformity (GU/%), and growth speed (GS/% etmal^{-1}). The experiment was arranged in three replications, with each replication consisting of 100 seeds.

The characteristics of pollinated papaya fruits were evaluated using both qualitative and quantitative approaches. Fruits selected for analysis had reached the physiological ripening stage. Upon full ripening, each fruit was transversely sectioned to a thickness of 5 cm to facilitate detailed assessment. Qualitative traits assessed included fruit shape (FS), flesh color (FC), cavity configuration (CC), flesh texture (FT), and aroma (Ar). Quantitative traits focused on organoleptic and reproductive aspects, including fruit sweetness (FS/°Brix), flesh thickness (FT/cm), seed number per fruit (SNpF), 100 seed weight (SW/g), and fruit water content (FWC/%). The thickness of the flesh is measured by peeling the fruit first, then measuring the thickness on 4 different and opposite sides. Quantitative parameters is measured in three replicates.

Quantitative data on pollen quality, seed germination, and fruit characteristics were analyzed using analysis of variance (ANOVA),

followed by mean separation or post hoc test with Duncan's Multiple Range Test (DMRT) at a 5% significance level using the SPSS application v.28. Qualitative observation data were presented descriptively in tabular form, while the daily progression of normal seedling germination over a 14 day period was illustrated graphically.

RESULTS AND DISCUSSION

After going through a long research process, this study was able to provide several important information. First, it is the type of papaya flower sex phenotype in the Calina/California cultivar, especially the consequences for seed germination and fruit quality when controlled/artificial pollination is carried out on each type of flower that has previously been determined to be male and female. Second, it is important information related to the quality of pollen in each type of flower that can act as a pollen contributor or male flower. And third, what pollination scheme should be used by farmers to achieve certain flower characteristics.

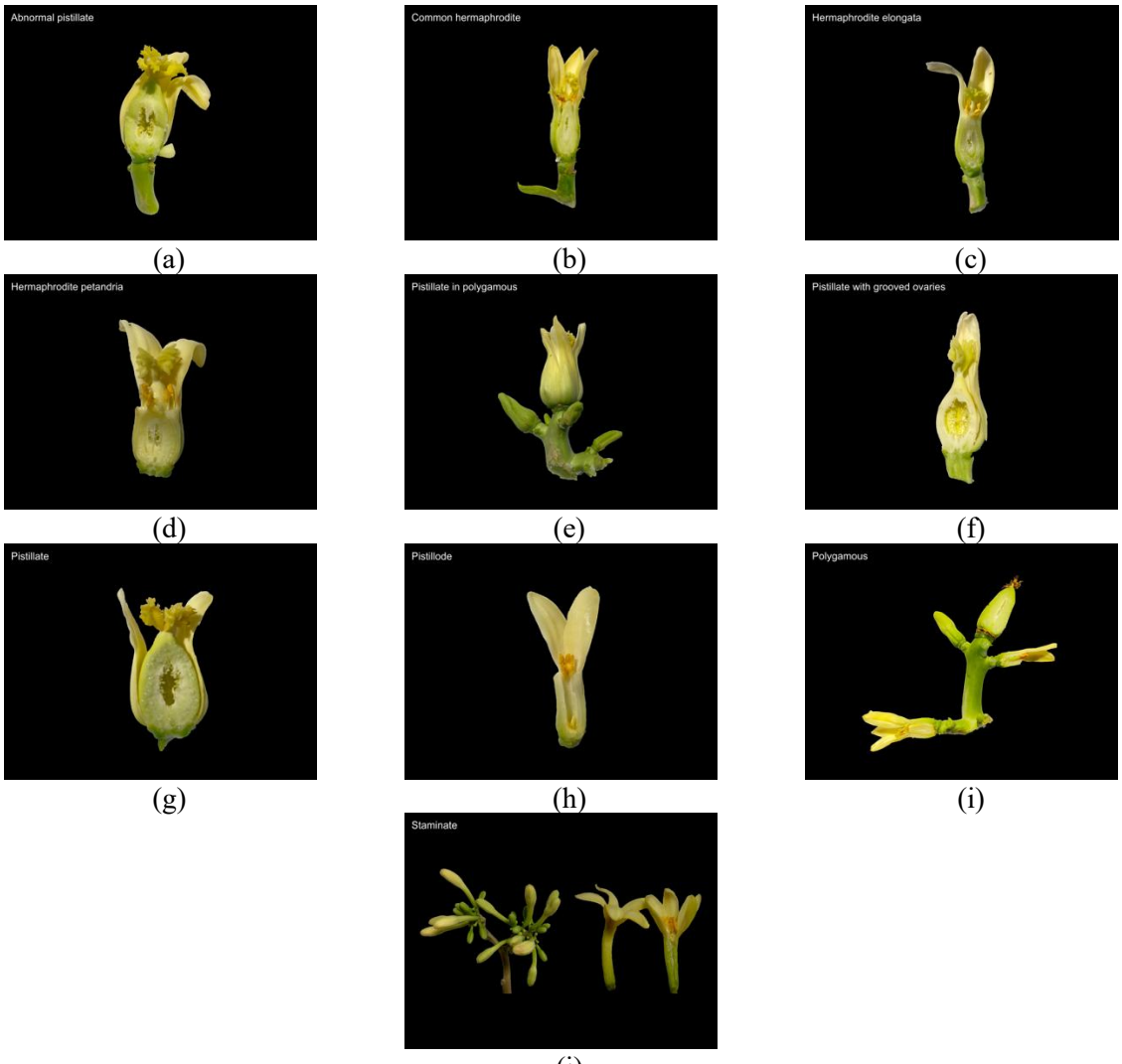


Figure 1. Papaya flowers used in controlled pollination, a: abnormal pistillate, b: common hermaphrodite, c: elongated hermaphrodite, d: petandria hermaphrodite, e: pistillate in polygamous, f: pistillate with grooved ovaries, g: pistillate, h: pistillode, i: polygamous, and j: staminate

In the initial stage to find out how many types of flowers can be found, 11 types of flowers were found including 1 abnormal male flower. The flowers found were abnormal pistillate, common hermaphrodite, elongated hermaphrodite, petandria hermaphrodite, pistillate in polygamous, pistillate with grooved ovaries, pistillate, pistillode, polygamous (with 3 flower bases in it, namely male, female, and hermaphrodite), and staminate as can be observed in figure 1.

Abnormal male flowers (abnormal pistil lodes) are not used in pollination because they have very low pollen viability as can be seen in table 2, abnormal male flowers have a greater chance of sterility and also high genetic incompatibility, abnormalities in endogenous hormone synthesis are one of the causes of this (Jia *et al*., 2023). This research was also able to show that variations in flower sex phenotypes, especially flowers that have male sex in the form of pollen, also have different levels of variation in viability and pollen germination capacity.

Table 2. Viability and Germination Rate of Papaya Flower Pollen

Male flower type	Pollen viability (%)	Germination rate (%)
Staminate	78,33±7,86^{abc}	72,35±1,21^{a}
Pistillode	75±6,32^{bc}	67,36±0,78^{b}
Abnormal pistillode	21.33±6,43^{d}	17,9±1,01^{d}
Pistillode in polygamous	73±5,32^{bc}	66,91±1,09^{b}
Intermediate	62±5,62^{cd}	59,7±1,24^{c}
Hermaphrodite	86,16±5,26^{a}	76,86±1,00^{a}
Hermaphrodite petandria	83,83±4,8^{ab}	71,96±1,06^{a}
Hermaphrodite elongata	85,83±7,60^{a}	75,11±0,93^{a}
Hermaphrodite in polygamus	63,66±6,94^{cd}	60,9±1,15^{c}
Mean	69,79	63,23
F	71,42**	287,61**
C/V	5,12	1,68

Based on the data on pollen viability and germination rate (Table 2), we can understand that hermaphroditic flowers have a fairly high average pollen viability of more than 80%, as well as a fairly high pollen germination power of more than 70% except in hermaphroditic flowers in polygamous plants. This is in accordance with the fact that hermaphrodite flowers on papaya have a higher chance than other types of flowers in forming fruit (Ming *et al*., 2007), Moreover, hermaphroditic flowers have a mechanism for self-pollination in forming fruit and also cleistogamous (Damasceno *et al*., 2009). If we look at it, apart from hermaphrodite flowers, staminate and pistil lode flowers also have good pollen viability and germination rate to support pollination. The greater pollen viability and germination, the greater chance of success in the pollination process and fruit formation (Sulusoglu & Cavusoglu, 2014).

Pollen viability and pollen germination in papaya flowers are closely related, with viability reflecting the percentage of viable,

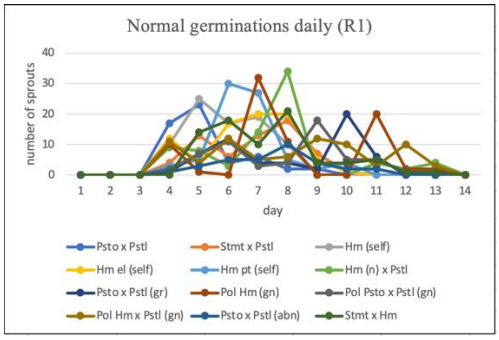
physiologically functioning pollen, while germination indicates the pollen's ability to actually form a pollen tube. Generally, higher pollen viability leads to higher germination, although both are also influenced by environmental factors, flower type, and the pollen's physiological condition (Twinkle *et al.*, 2025). Thus, these two parameters complement each other in assessing the potential for male fertility and the success of the papaya pollination process. In this condition, to overcome the lack of pollen sources if the flower population tends to have female flowers, farmers should be able to plant or provide special gardens to grow papaya with a tendency for male flowers as a pollen source.

Table 3. Papaya Seed Germination in The Context of Quantity Success

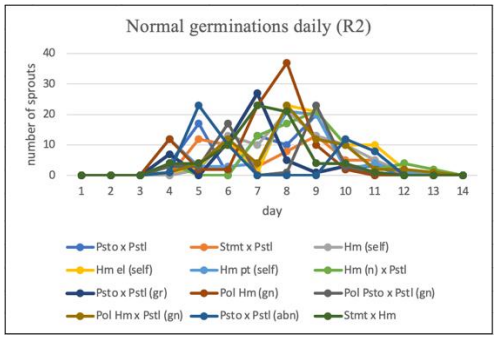
Scheme	NG	AG	DS
1	62,33±8,02^{abc}	3,80±0,73^{bc}	2,30±0,20^{abc}
2	63,33±8,08^{abc}	3,07±0,16^{c}	2,39±0,15^{ab}
3	81,66±6,02^{a}	2,75±0,63^{c}	1,94±0,22^{c}
4	81,33±2,51^{a}	2,77±0,84^{c}	1,96±0,14^{c}
5	73,66±2,51^{a}	3,43±0,30^{bc}	2,10±0,08^{abc}
6	74±3,60^{a}	3,46±0,86^{bc}	2,06±0,16^{abc}
7	47,33±13,31^{cd}	4,59±1,03^{abc}	2,43±0,30^{a}
8	79,33±8,08^{a}	2,72±0,30^{c}	1,98±0,39^{bc}
9	52,66±2,88^{bcd}	4,95±0,60^{ab}	2,30±0,13^{abc}
10	72±3,60^{a}	3,26±0,46^{bc}	2,18±0,03^{abc}
11	38,33±13,65^{d}	5,54±1,09^{a}	2,46±0,09^{a}
12	78,66±8,02^{a}	2,85±0,70^{c}	1,99±0,33^{bc}
Mean	67,02	3,60	2,17
F	10,70**	5,37**	2,43*
C/V	11,39	19,55	9,93

From the aspect of seed germination, we can understand that there are differences in the ability of seeds from fruit resulting from controlled pollination when viewed from the average number of normal sprouts (NG), abnormal sprouts (AG), and dead/non-germinating seeds (DS). The highest normal germination rate is achieved by fruit resulting from self-pollination by hermaphrodite flowers (scheme 3), the highest abnormal germination rate and the deadest seeds are seeds from fruit resulting from pollination of male flowers with rudimentary pistils with abnormal females (scheme 11). These three tests indicate the physiological quality of seeds. Normal germination indicates seeds with healthy embryos capable of growing into full-fledged plants, thus serving as a primary indicator of seed germination and vigor. Abnormal germination indicates viable seeds that are physiologically or genetically damaged and therefore unable to germinate normally in the field. Meanwhile, dead seeds reflect seeds that have lost their viability and are unable to germinate at all. Comparing these three components provides a comprehensive overview of the viability, vigor, and physiological quality of seeds within a population (Rahayu & Suharsi, 2015).

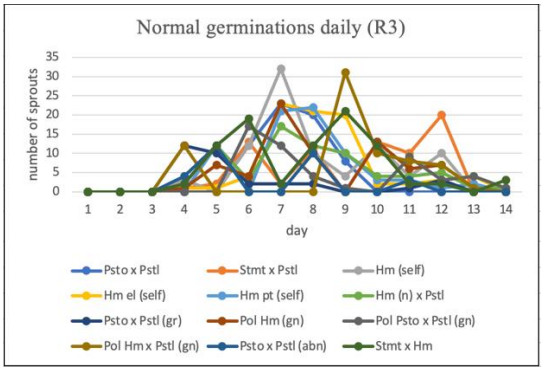
This observation is important to be used as a consideration by papaya seed producers to find out which pollinated fruit provides a high percentage of successful germination, because it will increase efficiency in seed production, regardless of the genetic stability passed down to the propagated population. Each seed from the fruit resulting from controlled pollination showed different daily normal germination rates as can be observed in Figure 2, on average the seeds began to show optimal normal germination from day 4 to day 10 (in three replications) but started to decrease in the 9th to the 10th day, although some seeds also showed germination on day 3. Almost all seeds from hermaphrodite fruits showed a high average normal germination rate during the 14 days of germination observation. Seeds with abnormal germination still have the potential to germinate normally, but at a slower rate. This can be caused by physical damage, failure of imbibition, metabolism (Fu *et al*., 2024), and in papaya seeds because there is still coumarin which inhibits germination (Chen *et al*., 2019).



(a)



(b)



(c)

Figure 2. Number/increase in the number of normal daily sprouts, a: replication 1, b: replication 2, and c: replication 3

Differences in the number of normal seedlings in various types of papaya fruit resulting from controlled pollination indicate variations in the physiological quality of seeds resulting from different genetic combinations and parental flower types. Flower types with better compatibility of male and female gametes generally produce seeds with fully developed embryos, resulting in a higher percentage of normal seedlings. Conversely, flower types

with hormonal imbalances, gamete incompatibility, or less viable pollen tend to produce seeds with weak or incompletely developed embryos, which reduces the number of normal seedlings.

Table 4. Papaya Seed Germination Characteristics

Scheme	MGC (%)	GR (%)	DWNS (g)	VI (%)	GS (% etmal-1)
1	76,66±9,45^{abc}	62,33±8,02^{ab}	0,55±0,04^{cd}	34,28±4,41^{cd}	9,65±0,86^{abc}
2	72,33±7,50^{bc}	63,33±8,08^{ab}	0,72±0,04^{a}	45,81±5,84^{bc}	8,16±0,24^{bcd}
3	89±5,29^{a}	81,66±6,02^{a}	0,72±0,05^{a}	59,34±4,38^{a}	11,08±1,25^{ab}
4	89±3,46^{a}	81,33±2,51^{a}	0,72±0,02^{a}	59,10±1,82^{a}	9,73±0,93^{abc}
5	85±2,64^{ab}	73,66±2,51^{a}	0,65±0,03^{abc}	48,12±1,64^{ab}	10,04±0,19^{abc}
6	86±5,29^{ab}	74±3,60^{a}	0,70±0,02^{a}	52,04±2,53^{ab}	9,40±0,52^{abc}
7	68,66±16,01^{c}	47,33±13,31^{bc}	0,55±0,05^{cd}	26,34±7,411^{d}	7,46±1,13^{cd}
8	86,33±9,71^{ab}	79,33±8,08^{a}	0,67±0,07^{ab}	53,68±5,46^{ab}	11,46±2,28^{a}
9	77±6,24^{abc}	52,66±2,88^{bc}	0,52±0,01^{d}	27,38±1,50^{d}	7,36±0,81^{cd}
10	82,33±1,15^{abc}	72±3,60^{a}	0,59±0,02^{bcd}	42,96±2,15^{bc}	8,93±0,62^{abcd}
11	69,33±5,50^{c}	38,33±13,65^{c}	0,74±0,03^{a}	28,36±10,10^{d}	5,82±2,34^{d}
12	86,66±10,40^{ab}	78,66±8,02^{a}	0,63±0,03^{abc}	50,08±5,10^{ab}	10,69±1,11^{ab}
Mean	80,69	67,05	0,65	43,96	9,15
F	2,74*	10,54**	10,60**	17,23**	5,68**
C/V	9,79	11,44	6,39	11,47	13,33

In the characteristics of seed germination, there is 1 parameter that shows no significant difference in results, namely the growth uniformity (GU). This is predicted because there are several factors such as seed condition, testing environment, and also different levels of coumarin compounds. Table 4 shows significant variation among papaya flower pollination schemes in various physiological parameters of seeds, Pollination schemes 3 and 4 showed the highest values for MGC (89%) and GR (more than 81%), indicating that the parent combinations in both schemes produced seeds with the best viability and germination ability. DWNS values also tended to be high in several schemes with high GR levels, indicating that well-germinated seeds were also able to form seedlings with greater biomass accumulation. Significant differences in GR, DWNS, and VI parameters (indicated by the F-test highly significant, $p < 0.01$) indicate that genetic factors of pollination combinations play an important role in the physiological quality of papaya seeds.

In general, seeds pollinated from more physiologically compatible flower types showed higher MGC, GR, and VI and greater germination rate (GS), indicating better initial vigor. Conversely, some schemes such as 7 and 11 had the lowest GR, VI, and GS values, indicating gamete incompatibility or imperfect embryo development due to less compatible parent combinations. This confirms that the success of controlled pollination in papaya not only determines fruit formation but also directly influences the physiological quality of the resulting seeds, so selecting the right combination of male and female flowers is key to producing seeds with high vigor.



Figure 3. Appearance of pollinated fruit result, scheme a: 1, b: 2, c: 3, d: 4, e: 5, f: 6, g: 7, h: 8, i: 9, j: 10, k: 11, and l: 12

Table 5. Qualitative Characteristics of Papaya Fruit

Scheme	FS	FC	CC	FT	Ar
1	The fruit is puffy at the bottom and the top is smaller	The near seeds are darker and the near skin is lighter	An intact pentagon slightly curved outwards like a round	Plain tender and there is a bitter taste at the end	It smells very good
2	The fruit is slightly bubbly but short	dark orange with no color gradation in the inner and outer edges	wide central cavity with a pentagonal shape	crispy on medium scale and slightly juicy	has a very strong smell (smell of a combination of papaya fruit and sugar)
3	The shape of the fruit is oval, smooth, the	The ivory color near the cavity is darker with a	Regular pentagons	Very soft, slightly juicy, no bitter taste	Very fragrant smell of fresh,

Scheme	FS	FC	CC	FT	Ar
	upper and lower side has almost the same size,	gradient of orange to light orange towards the skin			cooked and sweet papaya
4	The shape of the fruit is more oval than hm (self) and the lower side of the fruit is more pointed	The dark orange color around the cavity with the criteria is somewhat rounded and unevenly followed by gradations of orange and light orange	Regular hexagonal with small curves inclined to the oval	Soft, a little more water and not bitter	Has a scented smell below hm (self)
5	The shape of the fruit is slightly inflated at the bottom, the size of the fruit is almost the same on the top and bottom sides	The color is slightly dark in the edge cavity only partially and continued with a bright orange gradient on the edges	The pentagon is irregular, some are almost rounded and the other side is not the same length	Soft, tasteless, juicy	Smells good but a bit unpleasant combination of papaya and musty fragrance
6	The fruit is puffy at the bottom and followed by a cone. The shape of the fruit has a curve at the bottom of the fruit that puffs	Dark color near the cavity and bright orange towards the outer skin	The quaint cavities are precisely the same. Wider and larger cavities	Crunchy at the edges and soft in the middle near the cavity, slightly moisture content	It has a fairly fragrant aroma with a slight fragrance and not so pungent
7	The shape of the fruit is notched at the top, middle and bottom towards pointed. Notched fruits close to the shoots and indentations are found in the puffy part of the fruit	The color is slightly dark around the cavity curve and on the corner side of the cavity has a light orange color to the edge of the skin	Regular pentagon with one larger curve	Crunchy, slight moisture content	The smell in the fruit is not very fragrant
8	The shape of the fruit at the top is slightly notched on one side, the part of the bottom is not straight with the position of the fruit stalk	Dark orange color near the cavity and a not-so-contrasting orange gradation. Orange dominates	Irregular pentagons, each side is ridiculously shaped perfectly and tends to be oval	The outside is slightly dry and the inside is soft, no bitter taste	Not bad smell

Scheme	FS	FC	CC	FT	Ar
9	The fruit has a puffy shape on the upper and lower side and a slightly curved middle. Short fruit shape	Dark orange near the cavity then light orange followed by dark orange at the edges or near the skin	Pentagon with the shape of a widened Star	Regular tender and no bitterness	Quite fragrant with a fruit aroma that is not so thick
10	The shape of the fruit is oval and the bottom of the fruit is slightly pointed, the fruit has a rather flat character in the center of the fruit	The color is slightly dark near the fruit cavity and the dark orange spread is rather wide, followed by light orange at the edges	Rounded is not perfect, there is a pentagon-like curve but dominant to round	More tender and has a slightly bitter taste	Fresh Papaya Smell
11	The shape of the fruit is irregular, jagged on the surface of the skin, the central curve as a differentiator is not flat circular and the lower side of the fruit is concave	A deep color half the diameter of the fruit followed by a light orange gradation to the edge of the skin	Irregular pentagon, randomly following the shape of the fruit	Ordinary soft, not so much moisture content	It has a pleasant smell with the smell of papaya dominating over the smell of sugar
12	The fruit is oval and elongated in the absence of indentations on the surface	orange, with a thin gradation of light yellow in the outer and inner circles	narrow central cavity with a circular shape	crispy on medium scale and slightly juicy	Not too smelly

The fruit produced through the controlled pollination process showed a very diverse appearance visually (Figure 3), this shows that there is variation in fruit morphology when pollination is carried out on various types of flowers. directly, what can be clearly observed in the fruit is that there are differences in the shape of the fruit, the color of the flesh, the shape of the transverse slices, the shape and width of the cavity in the center of the fruit, and the surface of the fruit's skin. Fruit with a hermaphroditic female base has a circular and narrower central cavity, while fruit with a pistillate female base has a star-shaped and pentagonal central cavity with a fairly wide cavity. To ensure the differences accurately, qualitative and quantitative observations were carried out. Qualitative data from papaya fruit resulting from controlled pollination showed variations in several aspects (Table 5).

Table 6. Quantitative Characteristics of Papaya Fruit

Scheme	FS (°Brix)	FT (cm)	SNpF	SW (g)	FWC (%)
1	8,13±0,90^{de}	3,66±0,11^{fg}	3,72±0,35^{abc}	7,4±0,11^{bc}	79,66±1,52^{a}
2	20,33±1,15^{a}	4,23±0,25^{defg}	3,39±0,05^{abc}	15,12±0,22^{a}	82,6±2,08^{a}
3	10,66±0,57^{bc}	5,06±0,45^{abcde}	4,66±0,37^{a}	8,18±0,27^{bc}	71,33±3,51^{bc}
4	11,43±0,58^{b}	4,93±0,25^{bcde}	3,56±0,24^{abc}	7,54±0,10^{bc}	70±1,73^{c}
5	9,13±0,11^{cd}	4,53±0,61^{cdef}	3,62±0,18^{abc}	8,3±0,07^{bc}	73±2^{bc}
6	7,8±0,52^{de}	6,23±0,70^{a}	3,33±0,48^{bc}	8,55±0,10^{bc}	82,33±2,51^{a}
7	7,5±0,5^{de}	6,03±0,35^{ab}	3,60±0,06^{abc}	8,86±0,18^{b}	77±1,73^{ab}
8	7±1^{e}	4,13±0,05^{efg}	3,62±0,09^{abc}	8,01±0,17^{bc}	73±2,64^{bc}
9	7,9±0,36^{de}	3±0,52^{g}	1,53±0,76^{d}	0,64±1,11^{d}	82,66±3,78^{a}
10	8,33±0,28^{de}	4,1±0,36^{efg}	2,61±1,32^{cd}	5,13±4,44^{c}	82,33±2,51^{a}
11	10,16±0,76^{bc}	5,56±0,92^{abc}	3,99±0,18^{ab}	12,17±0,19^{a}	83±1,73^{a}
12	18,66±1,15^{a}	5,46±0,25^{abcd}	3,63±0,05^{abc}	14,11±0,37^{a}	71,66±2,08^{bc}
Mean	10,58	4,73	3,44	8,67	77,38
F	105,74**	12,56**	6,97**	25,05**	14,14**
C/V	6,98	10,01	14,45	15,41	3,12

The characteristics of papaya fruit are very important in the production/cultivation of papaya plants, because they determine the selling price and market interest. The market prefers fruit from self-pollinated hermaphrodite flowers (Fernandes *et al*., 2022), because it has a more uniform, oval shape, a narrow central cavity, is sweet, and has thick flesh. Even with the same cultivar, namely Calina/California, which is assumed to have the same genotype, pollinating several types of flowers with male, female and hermaphrodite bases, can produce fruit with various characteristics, not only in shape but also in taste paramaters (Table 6.).

Differences in the shape and flavor of papaya fruit produced by pollination of different flower types within a single cultivar are caused by variations in flower morphology and physiological influences during fruit development. Female flowers have rounded ovaries, producing round shaped fruit, while hermaphrodite flowers have elongated ovaries, producing oval or pyriform fruit. Although derived from the same genotype, differences in pollen origin and pollinated flower type can affect the activity of growth hormones such as auxin and gibberellin, which play a role in the formation of fruit flesh tissue, sugar accumulation, and water content (Khaleghi *et al*., 2021). Consequently, developing fruit exhibits variations in shape, flavor, and texture, reflecting the physiological influence of flower type and the role of pollen on fruit quality even in the absence of genetic differences between varieties.

in several previous studies including those conducted by Ávila-Hernández *et al*. (2023) stated that papaya fruit originating from self-pollination of hermaphrodite flowers is the sweetest fruit, but in this study, schemes 1 and 12 show the sweetest fruit, even almost 2 times sweeter than hermaphrodite. This is a discovery and an opening for further research, because farmers rarely pollinate staminate flowers, and even prefer to cut it down or cook the flowers. In scheme 12, hermaphrodite flowers are used

as female flowers by removing their stamens before anthesis and then pollination by staminate flowers, also producing fruit with a high level of sweetness, likely due to a genetic combination that favors carbohydrate accumulation during maturation.

Flesh thickness (FT) and seed weight (SW) also varied significantly ($p < 0.01$), with schemes 6 and 7 showing thicker flesh, while schemes 2 and 12 produced the heaviest seeds, indicating the influence of pollination on endosperm and embryo development. Meanwhile, fruit water content (FWC) was relatively high in most schemes (around 77–83%), with the highest value in scheme 11 (83%), indicating that the fruit from these pollinations had a more optimal physiological maturity level. Overall, these results show that variations in pollination combinations have a strong influence on the physical and physiological quality of papaya fruit, where certain parent combinations can improve fruit quality both in terms of taste and potential seed viability.

From this research, we can understand that the characteristics of pollen quality, seed germination, and also the quality of papaya fruit are not always determined by genotypic recombination through breeding and genotypic diversity through cultivar types and the environment, but the variation can also be influenced by the type of papaya flower sex phenotype and the combination of pollination between the flowers. This information can be used by farmers and breeders to target fruit with desired characteristics simply by arranging controlled pollination of several types of flowers.

CONCLUSION AND RECOMMENDATIONS

This study shows that phenotypic variation of flower sex in California papaya (*Carica papaya* L.) significantly affects pollen quality, seed germination, and fruit characteristics when pollination is carried out by using various pollination schemes. Hermaphroditic flowers, particularly the normal and elongate types, have the highest pollen viability and germination, which supports successful pollination and the formation of fruit with the best quality. Self-pollinated fruit from hermaphroditic flowers produces high levels of seed germination, fruit vigor, and sweetness, as well as uniform fruit shape, making it more desirable in the market. In contrast, combined pollination between certain male and female flowers results in variations in shape, flesh thickness, water content, and lower seed quality. These findings confirm that regulating combined pollination between flower types can be used as an efficient strategy in seed production and improving fruit quality in California papaya without requiring genotypic differences between cultivars. Suggestions after conducting this research, farmers should be able to provide special gardens as pollen sources.

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CONTRIBUTION STATEMENT

AHA: Developed the research concept, directed/coordinated the research activities, and wrote the manuscript. BAFR, NF, RDP, and RCU: Conducted field research and conducted observations in the experimental units. NF and ANO: Inputted and analyzed the research data.

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