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Effect of light type and mechanical scarification on the germination of passion fruit seeds (*Passiflora edulis* var. *flavicarpa*)

Efecto del tipo de luz y escarificación mecánica en la germinación de semillas de maracuyá (*Passiflora edulis* var. *Flavicarpa*)

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Abstract

The physiological quality of seeds is essential for ensuring efficient agricultural production. This study evaluated the interaction between light type (LED, fluorescent, darkness) and mechanical scarification on seed germination and viability. A completely randomized design (CRD) with a 3 × 2 factorial arrangement assessed six treatments involving scarified and non-scarified seeds. Seeds collected from three locations were dried, pretreated with tap water to overcome dormancy, and evaluated using the Between-Paper Method (BP) in light chambers with 100 seeds per replication. A 1 % tetrazolium viability test was conducted on scarified seeds, incubated at 30 °C for 18 hours to confirm embryo viability. Germination percentages were calculated based on the number of normal seedlings per treatment. Statistical analysis revealed a significant interaction between light type and micropyle scarification ($p < 0.05$), demonstrating that the effect of scarification depends on the light conditions. Scarified seeds exposed to LED light achieved the highest germination percentage (93.5 %), while non-scarified seeds subjected to fluorescent light or darkness showed the lowest rates. Micropyle scarification significantly improved germination (66.5 % versus 44.08 % for non-scarified seeds). No direct correlation was found between germination and viability ($r = -0.88$), highlighting the influence of additional factors. Furthermore, seeds from the Zapallal bio-garden showed superior germination, likely due to favorable local conditions. These results confirm that *Passiflora edulis* var***. flavicarpa*** seeds are positively photoblastic, with germination strongly influenced by the interaction between scarification and light type.

Keywords: *Germination percentage, mechanical scarification, LED light, normal seedlings, seeds viability.*

Resumen

La calidad fisiológica de las semillas es fundamental para garantizar una producción agrícola eficiente. Esta investigación evaluó cómo la interacción entre el tipo de luz (LED, fluorescente y oscuridad) y la escarificación mecánica afecta el porcentaje de germinación y viabilidad de las semillas. Se empleó un diseño completamente aleatorizado (DCA) bajo un arreglo factorial 3×2, que incluyó seis tratamientos con semillas escarificadas y no escarificadas. Las semillas recolectadas de tres localidades se secaron y pretrataron con agua de grifo para superar la dormancia antes de ser incubadas en cámaras de luz bajo el Método del Entrepapel, con 100 semillas por repetición. Adicionalmente, se realizó una prueba de viabilidad con tetrazolio al 1 % en semillas escarificadas, incubadas a 30 °C durante 18 horas para evaluar la viabilidad del embrión. Los porcentajes de germinación se calcularon a partir del número de plántulas normales por tratamiento. El análisis estadístico

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reveló una interacción significativa entre el tipo de luz y la escarificación micropilar ($p < 0.05$), indicando que el efecto de la escarificación depende de las condiciones de luz. Las semillas escarificadas bajo luz LED lograron el mayor porcentaje de germinación (93.5 %), mientras que las semillas no escarificadas expuestas a luz fluorescente o mantenidas en oscuridad presentaron porcentajes más bajos. No se encontró correlación directa entre germinación y viabilidad ($r = -0.88$), evidenciando que alta viabilidad no garantiza necesariamente altos porcentajes de germinación. Además, las semillas provenientes del biohuerto de Zapallal mostraron un desempeño germinativo superior, probablemente debido a condiciones locales favorables. En conclusión, los resultados confirman que *Passiflora edulis* var. ***flavicarpa*** es fotoblástica positiva, y su germinación está significativamente influenciada por la interacción entre la escarificación y el tipo de luz.

Palabras clave: *porcentaje de germinación, escarificación mecánica, luz LED, plántulas normales, viabilidad de la semilla.*

Introduction

The species *Passiflora edulis* var. *flavicarpa* O. Deg. originates from Brazil. Regarding global production, it is mainly cultivated in South American countries such as Brazil, Peru, Ecuador, Colombia, Bolivia, and Venezuela. It is also grown in Australia, New Zealand, Hawaii, South Africa, and Israel (Betancur et al., 2014).

It is estimated that the genus *Passiflora* has more than 500 species, many of which produce edible fruits, flowers with exuberant beauty and great ornamental potential, and phytoconstituents for medicinal purposes. These characteristics represent the cultivation's potential for generating employment and income with an eye on the international market. Therefore, cultivating passion fruit and other cultivated and exotic Passiflora species is important with multiple potentialities in terms of food, ornamental, and medicinal uses (Junghans & De Jesus, 2017).

In recent years, this crop has gained significant economic importance according to the Diario Gestión (2022). In the current year, the demand for passion fruit juice increased by 10% compared to 2021, amounting to US$ 6.1 million in exports. According to the National Institute of Agricultural Research [INIA] (2019), 96.2 % of exported passion fruit is in juice form, while the remaining 3.8 % is raw fruit cooked in water or steam.

The yield of this crop has decreased in recent years due to the smuggling of low-quality seeds into Peru, which has affected exports. In 2018, this resulted in a 7 % drop compared to the US$ 40.9 million exported in 2017. This issue caused the degeneration of the creole variety of passion fruit, reducing its pulp quality and sweetness, which has negatively impacted small- and medium-scale producers (INIA, 2019). In this context, Angelini et al. (2021) highlight that using high-quality seeds (genetic, physiological, and sanitary) is essential in modern agriculture to produce quality mother plants in nurseries, ensuring successful crop production and improving food security.

Light is a crucial factor influencing seed germination and seedling emergence. Some species exhibit inhibited germination when exposed to light (negative photoblastism), while others are stimulated by it (positive photoblastism). Porras et al. (2020) emphasize the importance of light in the germination process for seeds with positive photoblastic behavior, which increases germination rates and reduces seed dormancy. However, some seeds germinate independently of light conditions, i.e., they can germinate in both light and darkness (Matilla, 2003, cited in Gutiérrez et al., 2011).

There are several studies on the influence of light on the germination process. These investigations encompass a variety of plant species, both wild and cultivated, in which several factors were analyzed in addition to light intensity, such as temperature, and relative humidity, among others. It is also important to understand how these factors interact and how they influence the seed germination process. In this regard, Wu et al. (2020) indicate the positive effect of light intensity on the seed root emergence process.

Regarding seed dormancy in *Passiflora* species, it is mentioned that this process is one of the limiting factors that significantly reduce germination rates, affecting seed quality and large-

scale crop productivity. The types of dormancy present in the genus are mainly mechanical dormancy due to the impermeable seed coat and the presence of the aril. Additionally, in some species, there is a combination of physical and physiological dormancy. In this regard, some of the most commonly used types of scarification are mechanical and chemical scarification, which, depending on the species, can be more effective. In the case of *Passiflora incarnata*, chemical scarification is effective in overcoming dormancy (Angelini et al., 2021).

In others, such as *Passiflora edulis*, mechanical scarification and removal of the aril are more effective in overcoming seed dormancy. Moreover, it is noted that germination testing in a dark environment is an effective pre-germination treatment for overcoming dormancy (Ministério da Agricultura, Pecuária e Abastecimento [MAPA], 2009). Mabundza et al. (2010) determined that freshly extracted seeds of *Passiflora edulis* exhibited a low germination percentage. However, various pre-germinative treatments, both physical and chemical, proved effective in reducing germination time by breaking seed dormancy. Similarly, Flores et al. (2020) found that mechanical scarification significantly contributed to increasing the germination percentage in seeds of *Euterpe precatoria*.

On the other hand, among the important morphological characteristics of the seed is the presence of dimples, which correspond to the roughness or depressions on the surface of the seed coats. These dimples influence the ability of the seed to absorb water and nutrients and its capacity to overcome dormancy and germinate efficiently. This suggests that seeds with more dimples have a greater ability to break dormancy, which is important for the rapid growth and establishment of seedlings (Rodriguez et al., 2020).

Other studies indicate that the interaction of gibberellic acid with light acts as a mechanism for breaking dormancy in seeds of *P. nitida* (Passos et al., 2004).

According to the type of germination analysis, two types of germination have been established: physiological germination and agronomic germination (Figure 1). Physiological germination focuses on the initial process where the seed breaks dormancy and the radicle emerges. This process involves physiological and biochemical changes within the seed. In studies related to seed germination evaluation (plant physiology), this type of germination is often analyzed (Hosseini et al., 2002; Finch-Savage & Leubner-Metzger, 2006; Rosabal et al., 2014; Steinbrecher & Leubner-Metzger, 2017).

Figure 1. Classification of germination types based on researcher's analysis.

Agronomic germination generally refers to the complete process from the emergence of the radicle to the establishment of the seedling, which includes the emergence of the cotyledons and the initial development of the seedling. From an agronomic point of view, it is noted that although a seed has emerged its radicle, if it does not develop into a seedling within the trial period, it is considered an abnormal seedling (Hosseini et al., 2002; International Seed Testing Association [ISTA], 2018; Hiega et al., 2021).

In this regard, understanding the physiological behavior of the seed would contribute to increasing the production of this crop, benefiting the entire production chain involved. Therefore, the primary objective of this research was to determine the effects of the interaction between types of permanent light (LED, fluorescent, and dark) and mechanical scarification of seeds (scarified and non-scarified) on germination percentages. Additionally, the specific objectives included determining which treatments yielded the highest germination percentages in passion fruit seeds, assessing whether the interaction between the type of light and the type of seed influenced the germination process, and evaluating whether mechanical scarification significantly increased the germination percentages of passion fruit seeds.

Materials and methods

Plant Material - Seed Provenance

The research was conducted at the "Miguel Paulette del Campo" Seed Laboratory of the Department of Plant Science at the Faculty of Agronomy of the National Agrarian University La Molina, and at the National Seed Research Laboratory (LANIS) of the National Institute of Agrarian Innovation, both located in the metropolitan area of Lima, in the district of La Molina.

The biological material (botanical seeds) of *P. edulis* var. *flavicarpa* was obtained from the harvest of fruits from the INIA experimental center (La Molina) and the bio-garden of Zapallal (Puente Piedra), as well as from the purchase of fruits from the Megamercado Huamantanga supply center (Puente Piedra). The fruits were sourced from both the INIA experimental center and the Zapallal bio-garden at commercial maturity or harvest stage. Similarly, the fruits were obtained from the Megamercado Huamantanga supply center (Figure 2).

The fruits were harvested 50-60 days after anthesis, equivalent to 7-8 months after sowing, exhibiting the characteristic yellow coloration of ripe fruits, as indicated by Amaya-Robles (2009 -

Figure 2. Fruits collected for the extraction of Passiflora edulis var. flavicarpa seeds from the places of provenance. a) Fruits obtained from INIA, La Molina fields (1,2,3) b) Fruits obtained from the bio-garden of Zapallal, Puente Piedra (7, 8) c) Fruits obtained from Huamantanga market in Puente Piedra (4,5,6)

2010). Subsequently, the seeds were extracted for further washing and drying. The aril was removed using coarse sand to facilitate the detachment of this structure through friction. The seeds were then exposed to ambient temperature of 19 °C - 20°C for one hour. Finally, they were placed in pre-labeled Petri dishes for the germination tests (Table 1). The seeds that could not undergo germination tests on the same day of extraction and drying were stored in a refrigerator at 5 °C to maintain their internal moisture and prevent prolonged dehydration.

Table 1. Treatments Established for Germination Tests

Treatments	Study factors	
	Light type	Seed type as a function of scarification
T1	LED	Scarified seeds
T2	LED	Non-scarified seeds
T3	Fluorescent	Scarified seeds
T4	Fluorescent	Non-scarified seeds
T5	Without light	Scarified seeds
T6	Without light	Non-scarified seeds

Establishment of the Units of Analysis

Small transverse incisions (corresponding to 50 % of the total seeds, equivalent to 1 200 seeds) were made on previously moistened seeds near the micropyle (a form of mechanical scarification) to facilitate radicle emergence (Figure 3) A scalpel, tweezers, nail clippers, and a stereoscope were used for this procedure. The process of seed soaking or imbibition was conducted by moistening the paper towel (between-paper method) to ensure the activation of the germination process.

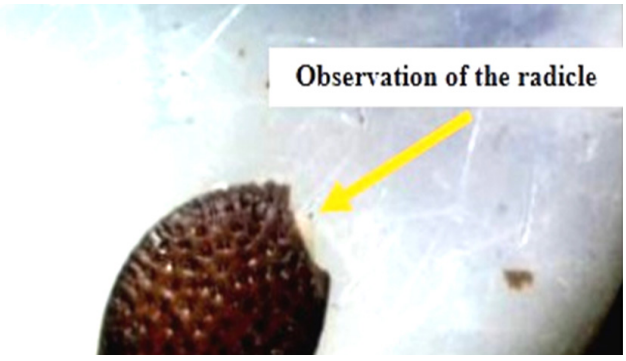


Figure 3. Micropylar region of the seed (basal zone) cross-section detail

As indicated by ISTA (2016), the seeds were placed between a double layer of filter paper (interleaved), and subsequently distributed on rolled paper towels, which were placed vertically inside plastic bags within germination chambers. Light watering was applied every three to four days to maintain the moisture of the paper and promote seed germination (Figure 4).

Seed Germination Test

The treatments were designed based on the type of light (LED, fluorescent, and dark) and the type of seeds (with and without micropylar scarification). Three to four evaluations per treatment were conducted over 28 days. In some cases, the evaluation period was extended due to the prolonged germination process of the seeds. In several treatments, 50 % of the total seed germination was achieved by day 28. The tests were performed at a constant temperature of 25 °C or within the optimal range of 20 °C to 30 °C for *Passiflora edulis* in germination chambers (MAPA, 2009).

The treatments under LED light were conducted in a germination room (dry room) equipped with sensors (data loggers) that recorded temperatures of 25.5 °C (outside) and 25.9 °C (inside), with a relative humidity of 32 %. Additionally, the observed photoperiod was 12 hours of light/12 hours of darkness. The dark treatments were also carried out in the same environment; however, they were covered with two layers of black plastic (Figure 4).

In the case of treatments with fluorescent light, these were conducted in a germination chamber equipped with a 100-watt fluorescent bulb, and a maximum-minimum thermometer was placed to record the temperature during the testing period. The photoperiod was 24 hours, meaning the seeds were exposed to light throughout the entire day. To maintain the moisture of the seeds and prevent their dehydration due to constant light exposure for an average of three weeks, frequent watering with distilled water was carried out every other day (Figure 4).

Normal seedling determinations were defined based on the standard criteria established in the ISTA (2016) and the ISTA (2018).

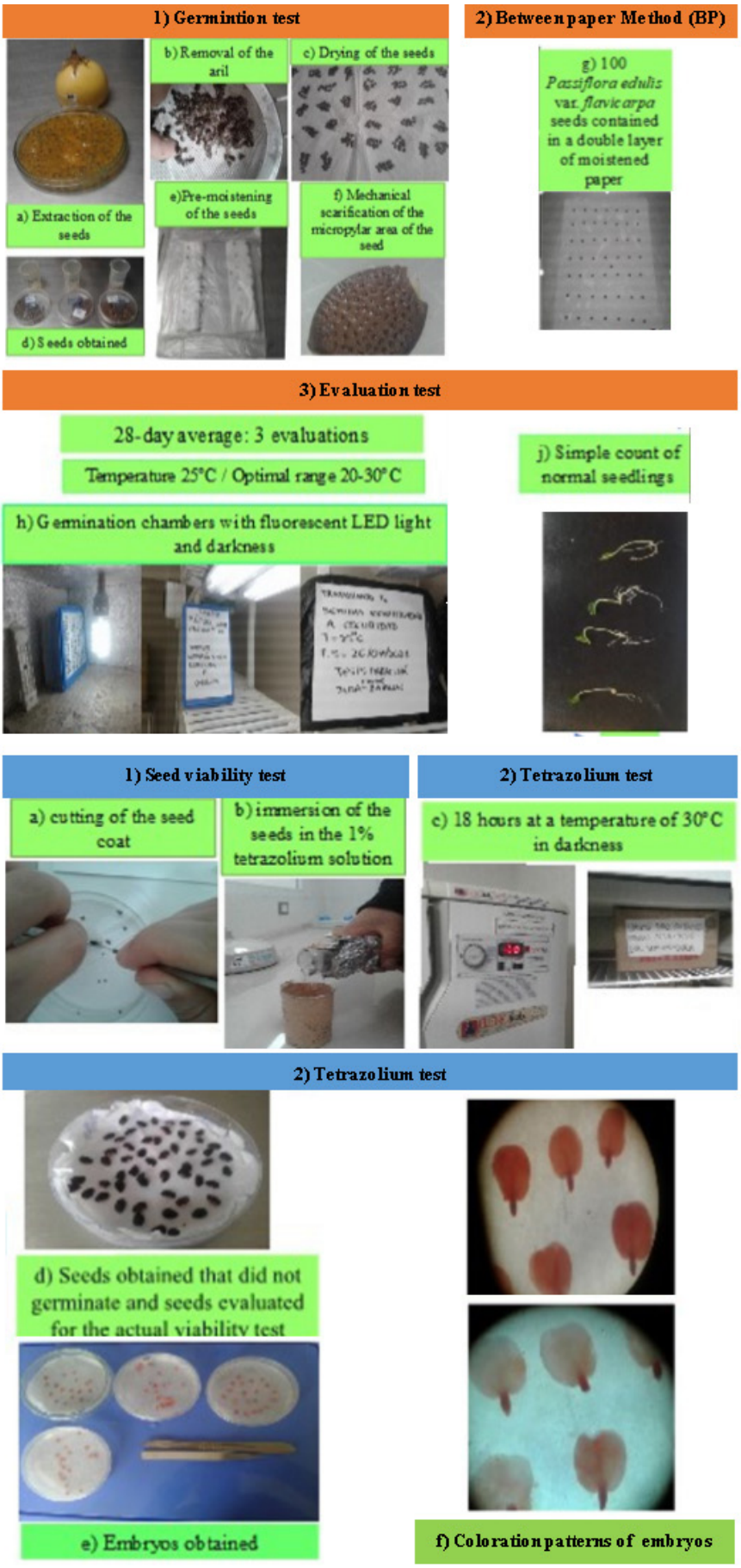


Figure 4. Schematic diagram of the study's methodological procedure

Seed Viability Test

The viability test was conducted using tetrazolium salt. This test was performed on seeds that did not germinate during the germination test to evaluate the longevity of the seeds. For this test, a representative sample of 100 seeds per replicate was taken, following the methodology described by Costa et al. (2016). Four repetitions per treatment were conducted using seeds from the three places of origin.

The protocol guidelines for *Passiflora edulis* were adapted by incorporating a pre-treatment consisting of pre-moistening the seeds using the between-paper method (ISTA, 2016; MAPA, 2009) for one week. This pre-treatment facilitated the softening of the seed coats to ease the cutting process. Longitudinal cuts were made with a scalpel between the two layers of the seed coat, and peripheral cuts (around the seed covering) were performed using nail clippers. These cuts were made carefully to break the seed coat to extract the embryo. This extraction was carried out with the help of thin-tipped laboratory tweezers (Figure 4).

The embryos along with the endosperm tissue obtained, were placed in Petri dishes lined with paper moistened with distilled water. Once the required number of embryos was prepared, they were transferred to a beaker covered with kraft paper, to which a 1 % tetrazolium solution was added. The beaker was then covered with kraft paper. Subsequently, the setup was placed in a germination chamber for 18 hours at a temperature of 30 °C (ISTA, 2003).

For the evaluation, the coloration patterns of both the embryo and the radicle were examined. According to the guidelines provided by ISTA (2003) in the Working Sheets on Tetrazolium Testing, non-viable tissue is determined starting from the midpoint of the radicle, measured from the tip, and the distal third of the cotyledon. In this context, the tone or degree of staining in the colored areas of the structures (embryo, radicle, and cotyledons) was taken into account.

Statistical Analysis

The data will be processed using Excel and Infostat software. A completely randomized design (CRD) with a 3 × 2 factorial arrangement was employed, including six combined treatments with scarified and non-scarified seeds, to evaluate the interaction between seed type and light type on germination percentage. A factorial ANOVA (Analysis of Variance) will be applied to determine the statistical significance of this interaction. Subsequently, Duncan's test will be used as a post-hoc method to identify significant differences between treatments and to analyze the effect of fruit origin on seed count and fruit weight.

Additionally, a linear regression analysis will be performed to determine the relationship between germination percentage and seed viability, taking into account the seed's origin. Furthermore, a MANOVA (Multivariate Analysis of Variance) will be conducted to assess the effect of fruit origin on multiple dependent variables simultaneously (fruit weight and number of seeds per fruit). For multiple group comparisons, Tukey's test will be applied. Finally, descriptive statistics (mean and standard deviation) will be calculated to summarize the main characteristics of the data.

Results and Discussion

Characterization of the Fruits

Regarding the morphometric measurements of fruits and seeds, the results indicate that the fruits from the Zapallal bio-garden exhibit a higher weight and, consequently, a greater number of seeds (Figure 5). To evaluate the effect of location on seed count and fruit weight, a MANOVA was performed. The results indicated significant differences among the three locations according to both Wilks' Lambda ($F = 5.94$, $p = 0.0052$) and Pillai's Trace ($F = 3.04$, $p = 0.0483$) (Table 2). Subsequent univariate ANOVAs revealed significant differences in seed count ($F = 10.45$, $p = 0.002$) and fruit weight ($F = 8.76$, $p = 0.005$) across locations (Table 3). Tukey's post-hoc test further showed that fruits from Zapallal had significantly more seeds (419 ± 85) and were significantly heavier ($308\ g \pm 30.8\ g$) compared to those from INIA and Mercado Huamantanga (Table 4).

Table 2. Multivariate Analysis of Variance (MANOVA) and Univariate ANOVA Results for Seed Count and Fruit Weight in *Passiflora edulis* var. *flavicarpa* Across Locations

Effect	Test Statistic	F-value	P-value
Location Effect	Wilks' Lambda	5.94	0.0052
Location Effect	Pillai's Trace	3.04	0.0483

Tabla 3. Univariate ANOVA Results for Seed Count and Fruit Weight in *Passiflora edulis* var. flavicarpa Across Locations

Effect	F-value	P-value
Seed Count (Location)	10.4	0.002
Fruit Weight (Location)	8.76	0.005

Tabla 4. Tukey's Honestly Significant Difference (HSD) Post-hoc Test Results for Seed Count and Fruit Weight in *Passiflora edulis* var. flavicarpa Across Locations

Comparison	Seed Count (p-value)	Fruit Weight (p-value)
Zapallal vs. INIA	< 0.001	0.003
Zapallal vs. Mercado Huamantanga	< 0.001	0.002
INIA vs. Mercado Huamantanga	0.120	0.250

These findings suggest a direct relationship between fruit weight and seed count, which aligns with various studies indicating that larger fruits provide more space for seed development, allowing a greater number of ovules to be fertilized and become viable seeds. Additionally, the greater availability of resources in larger fruits, such as nutrients and water, favors the development of a higher number of seeds. This relationship also reflects a reproductive strategy, as many species produce larger fruits with more seeds to enhance dispersion and species survival. In common agronomic crops such as passion fruit, tomato, and pepper, it is estimated that in approximately 70 % to 80 % of cases, there is a positive correlation between fruit size and the number of seeds (Dempsey & Boynton, 1965; Shobo et al., 2023).

Characterization of Seedlings and Seeds

Normal Seedlings and Abnormal Seedlings

Based on the morphological characteristics evaluated, normal seedlings of various sizes, ranging from small to large, were observed. Optimal morphological characteristics were

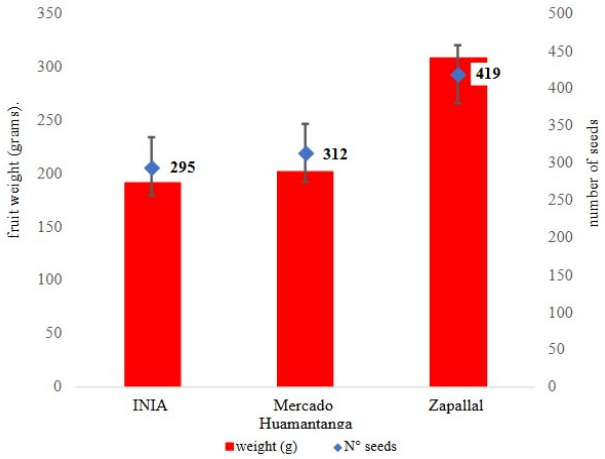


Figure 5. Morphometric relationship between fruit weight and seed number in Passiflora edulis var. flavicarpa.

identified, including cotyledons with a uniform green coloration. Similarly, the radicle size was variable, maintaining complete structures with no signs of primary infection. Hypocotyls were generally erect, without noticeable deformities (Figure 6). On the other hand, abnormal seedlings were mainly associated with the poor sanitary quality of the seeds, resulting in primary infections. These abnormalities were characterized by deformities in cotyledons, radicles, and hypocotyls. Secondary infections, mainly caused by fungi such as *Aspergillus* and *Penicillium*, were not included in this analysis (Figure 7).

Scarified seeds showed higher percentages of normal seedlings under all light conditions, with the LED light treatment achieving the highest percentage (90 % ± 2.5 %), followed by fluorescent light (85 % ± 3%) and darkness (70 % ± 4 %). In contrast, non-scarified seeds exhibited lower percentages of normal seedlings, with LED light being the highest (60 % ±5 %), followed by fluorescent light (55 % ± 4.5 %) and darkness (40 % ± 6 %). These results highlight that scarification has a positive impact on seedling quality under all light conditions. The highest percentage of abnormal seedlings was observed in non-scarified seeds exposed to darkness (60 % ± 4 %), while the lowest was recorded in scarified seeds treated with LED light (10 % ± 1 %) (Table 5).

These findings emphasize the significant role of scarification and light type in enhancing the

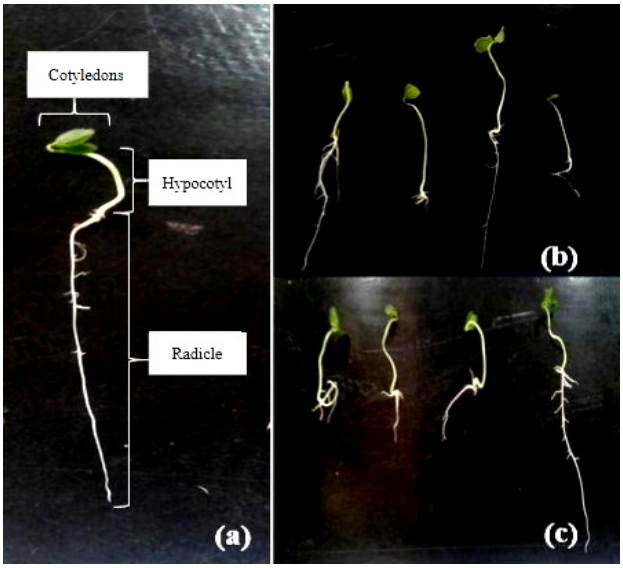


Figure 6. Observations of normal seedlings of *Passiflora edulis* var. flavicarpa under light conditions.

(a) Structure of a normal seedling under light conditions.
(b) Observation of the morphology of normal seedlings obtained during the evaluation of treatments.
(c) Observation of the morphology of normal seedlings obtained during the evaluation of treatments.

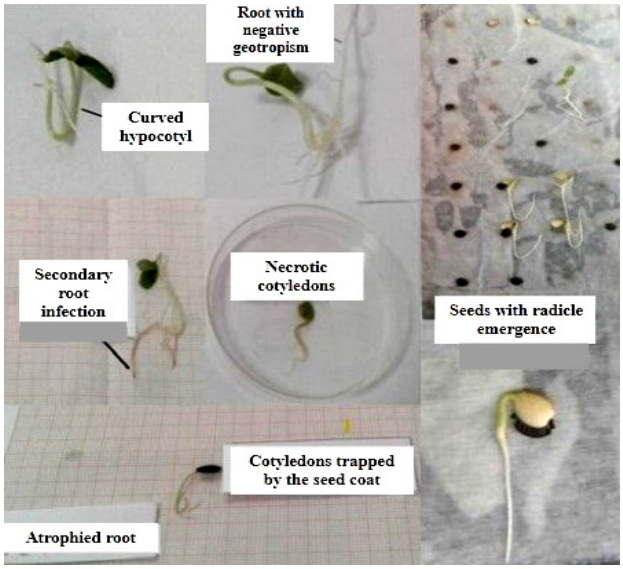


Figure 7. Observations of abnormal seedlings of Passiflora edulis var. flavicarpa

Note: Seedlings were considered abnormal if they did not develop primary leaves, hypocotyls, or radicles, according to ISTA (2018).

development of normal seedlings and minimizing abnormalities.

Germination Percentage

According to the results obtained, it was observed that for both the model and the interaction between the study factors, the p-value was lower than the calculated F-value. This indicates that at least one treatment had a different germination percentage at a significance level of 95 %. Therefore, it was confirmed that there was an interaction between the study factors. Subsequently, Duncan's test was performed to verify the presence of differences between treatments Table 6).

Significant differences were observed among the treatments (Table 7). The treatment involving seeds subjected to conditional scarification under LED light achieved the highest germination percentage compared to the other treatments (Figure 8). Similarly, it can be considered that the treatments with the lowest germination percentages were those conducted under fluorescent light conditions, both for scarified and non-scarified seeds (Figure 9). On the other hand, seeds without micropyle scarification that were exposed to LED light and dark conditions also exhibited lower germination percentages (Figure 10). Notably, the treatment involving scarification under LED light showed the highest germination percentage (93.5 %), highlighting the energy efficiency of seeds under this condition.

These results align with those reported by Sanoubar et al. (2018), who observed that LED light promotes efficient energy utilization in germination processes. Furthermore, Akbarian et al. (2016) recommend the development of LED lighting systems, emphasizing their effectiveness in producing high-quality seedlings with

Table 5. Germination percentages of *Passiflora edulis* var. flavicarpa seeds based on the interaction between light type and seed type

Treatment	Normal Seedlings (%)	Standard Deviation	Abnormal Seedlings (%)	Standard Deviation	Grouping
Scarified seeds + LED	90%	±2.5	10%	±1.0	A
Scarified seeds + Fluorescent	85%	3.0	15%	±1.5	A
Scarified seeds + Darkness	70%	±4.0	30%	±2.0	B
Non-scarified seeds + LED	60%	±5.0	40%	±3.0	B
Non-scarified seeds + Fluorescent	55%	±4.5	45%	±2.5	B
Non-scarified seeds + Darkness	40%	±6.0	60%	±4.0	C

Note 1: Different letters (A, B, C) indicate significant differences ($p < 0.05$) according to Duncan's test (or the statistical test used).
***Note 2**: This table shows the percentage of normal and abnormal seedlings. For germination percentages, see Table 7.*

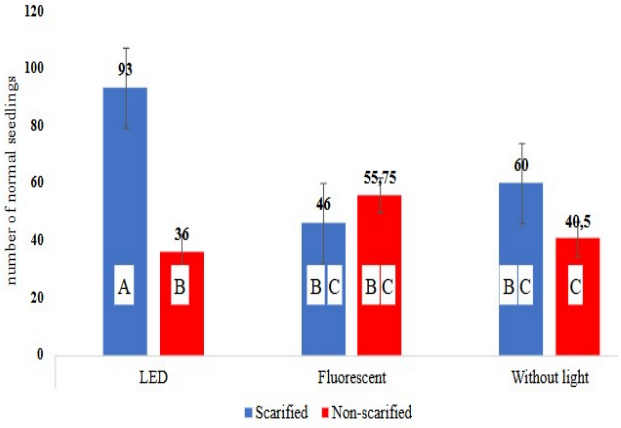
Table 6. Analysis of Variance: Model and study factors

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-value	P-value
Model	8638.21	5	1727.64	10.46	0.00
Type of light	1075.08	2	537.54	3.25	0.06
Seed type (scarified and unscarified)	3015.04	1	4.54	18.26	0.00
Type of light * Seed type	4548.08	2	2274.04	13.77	0.00

Table 7. Duncan's test for germination percentages based on the interaction between light type and seed type factors as a function of micropyle scarification.

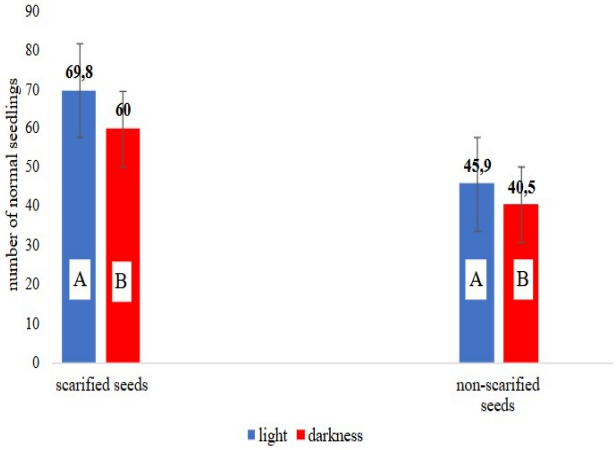
Treatments		Means	N	E.E	Grouping
Light type	Seed type				
LED	Scarified	93.5	4	6.43	A
Without light	Scarified	60.00	4	6.43	B
Fluorescent	Non-scarified	55.75	4	6.43	B C
Fluorescent	Scarified	46.00	4	6.43	B C
Without light	Non-scarified	40.50	4	6.43	B C
LED	Non-scarified	36.00	4	6.43	C

Note: This table shows the germination percentages. For seedling quality (normal vs. abnormal), see Table 5.



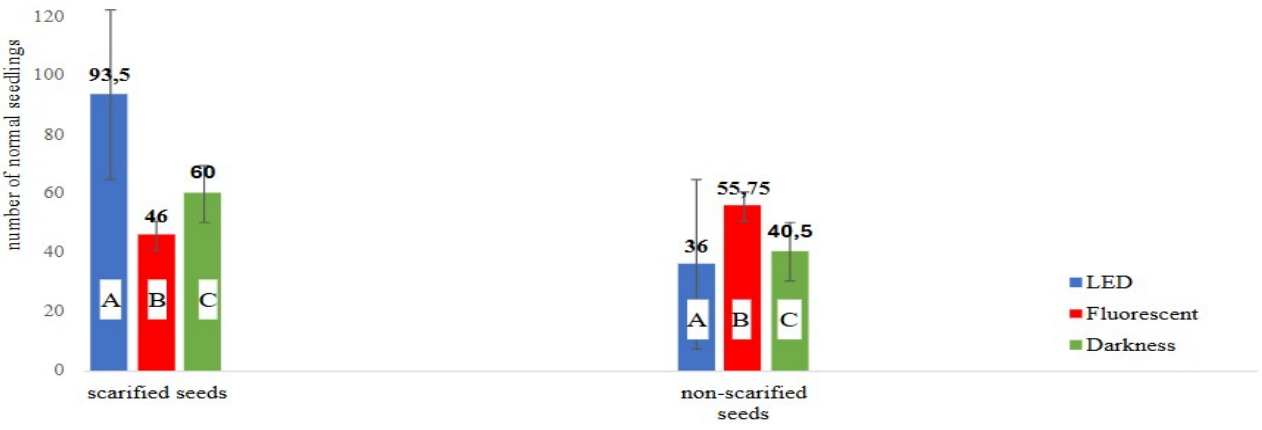
Legend: Different letters indicate significant differences according to Duncan's test ($p < 0.05$).

Figure 8. Germination percentages of Passiflora edulis var. flavicarpa seeds under LED, fluorescent, and dark conditions



Legend: Different letters indicate significant differences according to Duncan's test ($p < 0.05$).

Figure 9. Germination percentages of *Passiflora edulis* var. flavicarpa seeds with and without micropyle scarification under light and dark conditions



Legend: Different letters indicate significant differences according to Duncan's test ($p < 0.05$).

Figure 10. Comparison of germination percentages of *Passiflora edulis* var. flavicarpa seeds under fluorescent light and dark conditions, with and without micropyle scarification

characteristics such as greater stem diameter, higher fresh root weight, and lower incidence of morphological disorders, compared to seedlings grown under fluorescent light. Finally, the interaction between light conditions and micropyle scarification reinforces the importance of optimizing both physical and environmental treatments to maximize the germination of *Passiflora edulis* var***. flavicarpa***.

In this context, Liang et al. (2021) state that under LED light conditions, the quality of light—characterized by lower heat release and a more uniform distribution of light photons—positively influences the photosynthetic efficiency of seedlings.

Moreover, different combinations of irradiance, light quality, and photoperiods significantly affect the biomass of *Passiflora edulis* seedlings, reflected in increased size, a higher number of leaves, and greater production of antioxidant enzymes, flavonoids, and phenols. In this context, it is stated that under LED light conditions, the quality of light—characterized by lower heat release and a more uniform distribution of light photons—positively influences the photosynthetic efficiency of seedlings. Moreover, different combinations of irradiance, light quality, and photoperiods significantly affect the biomass of *Passiflora edulis* seedlings, resulting in increased size, a higher number of leaves, and greater production of antioxidant enzymes, flavonoids, and phenols (Liang et al., 2021).

Regression Analysis and Simple Linear Correlation Between Viability Percentage and Germination Percentage

The linear regression analysis revealed a significant negative relationship between viability percentage and germination percentage ($y = -4.1786x + 460.67$). This suggests that as the viability percentage increases, the germination percentage decreases, indicating that seeds with high viability do not necessarily exhibit high germination percentages. Conversely, seed lots with high germination percentages tend to have high viability. To analyze this relationship more accurately, it would be essential to include additional factors in the study, such as germination rate, environmental variation, seed vigor, dormancy type, storage conditions, and other relevant variables. Regarding the Pearson correlation coefficient ($r = -0.88$), it indicates a very strong negative correlation between the two variables. This means there is a close inverse relationship between viability percentage and germination percentage. On the other hand, a coefficient of determination (R^2) of 0.7756 indicates that 77.56 % of the variability in germination percentage can be explained by the viability percentage. This suggests that the linear regression model fits the data reasonably well (Figure 11).

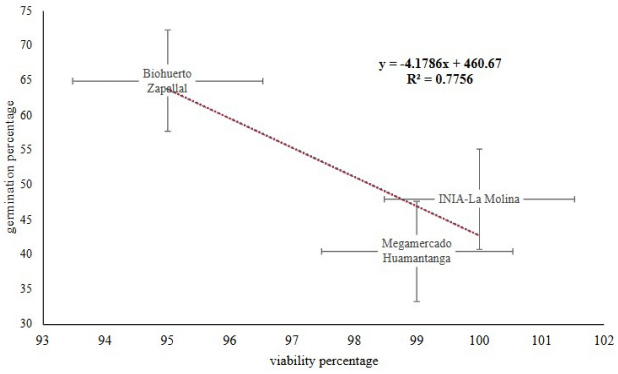


Figure 11. Correlation between viability and germination percentages for seeds of *Passiflora edulis* var. flavicarpa from three origins

This can be explained by the fact that certain passion flower seeds may exhibit physical or physiological dormancy, meaning they germinate rapidly under certain conditions (e.g., scarification or hormone treatment), but their intrinsic viability may be low due to internal mechanical damage affecting the embryo during harvest or processing. These damages may not initially affect germination, but reduce their long-term viability. Additionally, the genus *Passiflora* is diverse, and genetic variability between species or even between seed lots can influence their behavior. Therefore, some seeds may germinate quickly but have low viability due to specific genetic characteristics (Meletti et al., 2005; Carvalho & Nakagawa, 2012; Baskin & Baskin, 2014).

The results indicate that seeds obtained from the fruits exhibit a high viability of over 90 % (Table 8), both in fresh and stored seeds (Figure 12). Therefore, these results confirm those

of Vega-Corrales et al. (2022), who reported viability percentages of 85% and 94% in seeds of *P. biflora* and *P. adenopoda*, respectively, determining the seeds of these *Passiflora* species to be orthodox. In this context, Posada et al. (2014) determined the orthodox behavior of three *Passiflora* species: *P. edulis* f. *flavicarpa*, *P. ligularis*, and *P. edulis* f. *edulis*.

Table 8. Viability test results of seeds from different origins of *Passiflora edulis* var. flavicarpa

Location	Viabilty Percentage	Grouping
INIA La Molina Experimental Center	95 %	B
Huamantanga Market	99 %	A
Zapallal Community Garden	100 %	A
Mean	98 %	
CV	2.71 %	

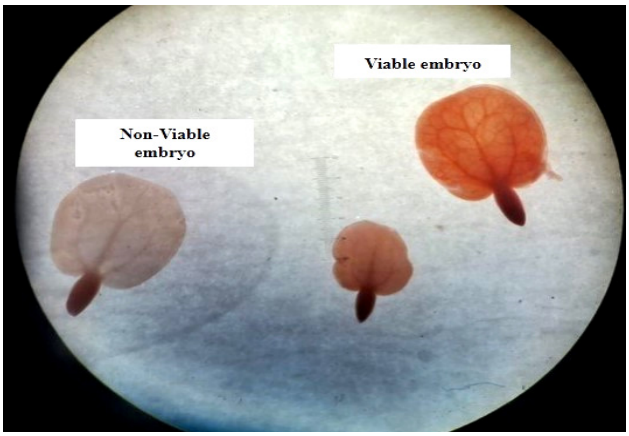


Figure 12. Observation of Viable and Non-Viable Embryos of *Passiflora edulis* var. flavicarpa.

Conclusions

According to the established objectives, it is concluded that there is a significant interaction between the type of light and mechanical scarification on the germination percentage of ***Passiflora edulis*** var. ***flavicarpa*** seeds. This result indicates that the effect of one factor depends on the level of the other, and they should not be analyzed separately.

- Under LED light, mechanically scarified seeds showed the highest germination percentage (95.5 %), while non-scarified seeds presented the lowest (36 %). This suggests that the combination of LED light and mechanical scarification is the most effective for promoting germination.
- Under fluorescent light, the difference between scarified and non-scarified seeds was less pronounced (46 % vs. 55.75 %), indicating that this type of light has a less marked effect on germination.
- In darkness, scarified seeds also showed higher germination (60%) compared to non-scarified seeds (40.5 %).

These results confirm that *Passiflora edulis* var. *flavicarpa* seeds respond positively to light (positive photoblastism), especially when combined with mechanical scarification. However, it is important to note that the origin of the seeds was not considered in this study, so future research is suggested to explore this aspect to better understand its influence on germination.

It is suggested that future studies conduct an analysis of the varietal purity of *Passiflora edulis* var. flavicarpa seeds to more accurately determine the correlation between the physiological quality of the seeds, their longevity, and the fruit collection site.

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Author Contributions

DMAO and CEFS: Conceived and designed the experiments. DMAO and EIH: Performed the experiments, interpreted the data and wrote the paper. DMAO: Conducted the data analysis and visualization of the data. CEFS and EIH: Supervising the research.

Conflict of interests

The authors declare no irreconcilable circumstances. Further, the final version of the manuscript was approved by all authors.

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