

Artificial diets for the rearing of *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Thripidae)

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Abstract

Ceratitis capitata (Wiedemann, 1824) (Diptera: Tephritidae) is a polyphagous insect responsible for severe damage to fruit crops worldwide. Control strategies require laboratory studies in which large quantities of individuals of this pest are required, thus requiring the implementation of mass rearing. The success of these rearing's is dependent on the use of artificial diets, which represent one of the main costs of this system. The objective of this study was to evaluate the growth and development of *C. capitata* under different artificial diets. The inoculation of *C. capitata* eggs was performed in artificial diets based on sweet potato, yam, carrots, pumpkin, and cassava, all raw and cooked, totalizing 10 treatments, with raw carrots being the control treatment. We observed the following biometric and biological variables of *C. capitata*: larval and pupal viability, fecundity, fertility and sex ratio, as well as pre-oviposition, oviposition, and adult lifetime. Promising results were obtained with sweet potato and pumpkin, providing larger and heavier insects, good fecundity and fertility, longer oviposition time, and greater longevity, whose results were similar or superior to those obtained with the raw carrot-based diet. In contrast, the raw cassava diet did not allow the larvae to hatch. Unsatisfactory results were also obtained with the raw and cooked cassava-based diets, making it unfeasible to recommend them for use in artificial diets for this insect. The artificial diets derived from raw or cooked pumpkin and sweet potato were efficient as carrot substitutes in artificial diets for *C. capitata*.

Keywords: fruit growing, insect farming, plant pests

Introduction

Fruit flies (Tephritidae) represent an important group of pest insects for agriculture worldwide, constituting one of the most economically damaging pests for this sector (Wang et al., 2017). Among the economically important tephritids, the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824), stands out (Deutscher et al., 2019), considered one of the most destructive pests in the world (Sciarretta et al., 2018). This multivoltine, highly invasive, and polyphagous species (Tsakireli et al., 2019) is native to the African continent and has spread to several regions of the globe, including South America (Alves et al., 2019).

This pest generates losses in different crops (Sciarretta et al., 2018) because it can infest more than 300 species of plants, depreciating the quality of the fruits and hindering their commercialization (Alves et al., 2019). In addition, in the absence of control, it can generate

losses of up to 100% in fruit production (Goldshtein et al., 2017).

Management strategies for the effective control of this pest insect have become a global need, driving several studies on this problem. Sterile insect technique (Nikolouli et al., 2020), mass rearing of parasitoids (Morera-Montoya et al., 2019), experimentation with the use of entomopathogenic microorganisms (Gava et al., 2021) and plant extracts (Benelli et al., 2021) are some of the strategies with potential for the control of *C. capitata* in the field and that require testing steps in the laboratory with the need for mass rearing of this pest insect. The success of these techniques depends on obtaining well-developed insects, which is directly related to the use of suitable artificial diets (Aceituno-Medina, 2019).

Artificial diets are used for the domestication, colonization, large-scale production, and maintenance of a large number of species under laboratory conditions

(Pascacio-Villafán et al., 2017). The development of diets for fruit fly rearing is dependent on several factors, most prominently the availability of suitable material for this purpose. One of the bottlenecks for the rearing of *C. capitata* is the absence of commercial products, requiring the production of this medium in the laboratory (Aceituno-Medina, 2020).

The production of these diets is usually based on plant materials, with other constituents added on a smaller scale. A recurrent food base for the preparation of these diets is carrots (Tanga et al., 2015; Majumder et al., 2020). However, nowadays, the use of low-cost and locally available ingredients has driven some research, with substantial and promising results being obtained for rearing tephritid species (Canale et al., 2015).

However, there is still a lack of studies on the formulation of artificial diets for rearing *C. capitata* in Brazilian entomological laboratories, especially with the use of more accessible and less expensive ingredients. In this sense, the objective of this research was to evaluate the growth and development of *Ceratitis capitata* under different artificial diets.

Material and Methods

The study was conducted in the Laboratory of Entomology (LEN) of the Center for Agricultural Sciences (CCA), Federal University of Paraíba (UFPB), Areia, PB, Brazil, in a room maintained at temperature $25 \pm 2^\circ\text{C}$, relative humidity of $70 \pm 10\%$ and photophase of 12 hours. The fruit flies (*C. capitata*) used in the experiment were from the rearing maintained in the Entomology Laboratory of the Federal University of Paraíba, CCA, Areia - PB.

Fruit fly rearing

The adults of *C. capitata* were kept in 20 x 30 x 20 cm cages shaded with *voil* cloth, placed on trays with water for egg collection. The adults were fed daily with a 10% water and honey solution, through a cotton wad placed on the top of the cage during the oviposition period. The collected eggs were placed on the artificial diet (Table 1) in plastic jars measuring 20 x 10 x 5 cm.

Table 1. Artificial diet for larval development of *Ceratitis capitata*.

Ingredient	Mass (g)
Brewer's Yeast	80.0 (16.53%)
Raw carrot	400.0 (82.64%)
Nipagin (Antifungal)	4.0 (0.83%)

Ceratitis capitata eggs were placed in the diet 24 to 48 hours after collection. After approximately 10 days, the containers containing the 3rd instar larvae were transferred to trays (34 x 34 x 14 cm) containing sterilized

sand to obtain pupae. The pupae were placed inside the cages in Petri dishes for the emergence of adults, thus restarting a new rearing cycle.

Artificial diets

The diets used in the treatments were prepared according to the percentages already used in the artificial diet (Table 1), replacing the raw carrot (*Daucus carota* L.) (control) by the plant sources: sweet potato (*Ipomoea batatas*), yam (*Dioscorea* spp.), pumpkin (*Cucurbita moschata*), cassava (*Manihot esculenta* Crantz). All plant sources were used in raw and cooked form. Therefore, each treatment consists of plant material, nipagin, and brewer's yeast. The cooking period for the cooked treatments was 30 minutes.

All treatments (raw and cooked) were ground in a blender, and then mixed and homogenized with the other ingredients of the artificial diet (brewer's yeast and nipagin).

The experiment was entirely randomized with 10 treatments (different artificial diets) and 10 repetitions. Each repetition was composed of 50 g of artificial diet, in circular plastic containers (250 cm³) covered with *voil*.

In each container, 50 viable *C. capitata* eggs collected 24 hours after oviposition were inoculated, totaling 500 eggs for each of the 10 treatments. After larval development, the containers were placed under sterilized sand to obtain pupae, which were then placed in circular cages (350 cm³) with one end covered with *voil* for oviposition of females, on trays with distilled water to collect eggs. The adults were fed with a 10% water and honey solution and egg-laying collected daily.

Variables analyzed

The number of pupae (NP), pupal weight (PWE) - performed on analytical scales, pupal width (PWI), and pupal length (PL) - using a digital pachymeter were evaluated. The larval viability (LV), pupal viability (PV), and egg-to-adult viability (EAV), determined by the ratio between the number of adults and the number of eggs, were also evaluated. From daily observation, the egg-to-adult (EAT), pre-oviposition (POT), oviposition (OT), and adult life (ALT) times were evaluated. The sex ratio (SR) was obtained by the ratio of the number of females by the total number of adults.

For egg fertility (Fert) evaluation, 30 eggs from the second day of oviposition were collected and transferred to Petri dishes with moist paper. The plates were then wrapped with film paper and kept in the BOD ($25 \pm 2^\circ\text{C}$) for hatching and recording the number of larvae after 72 hours (Dias et al., 2019).

The eggs were removed and stored daily until the end of the oviposition period of the females. In the end, the total fecundity (Fec) of each treatment was estimated by counting eggs in 1ml (volumetric pipette) taken from 10ml of the mixture of eggs and distilled water for each repetition. The counting was performed with the aid of a Zeiss Discovery V12 stereoscopic magnifier with a high-resolution camera attached to the Axiocam MRc5 system.

Data Analysis

The data were analyzed for normality by the Lilliefors test. In the case of normality, they were submitted to analysis of variance (ANOVA) and the means were compared by the Scott-Knott test. When normality was not observed, the data were submitted to Kruskal-Wallis analysis and the means were compared using Dunn's test. For both tests, an error probability of 5% was adopted.

Subsequently, Pearson's linear correlation coefficient matrix (r) was estimated between the biometric characteristics of pupae and the biological characteristics of *C. capitata* adults. The significance of r was verified using Student's t-test at 5% probability. The Fruchterman-Reingold algorithm (Fruchterman & Reingold, 1991) was used to elucidate the relationship between the studied variables and generate a layout, in which the proximity between traits is proportional to the absolute value of correlation between them (Elaoud

et al., 2021). Positive correlations were colored in green, while negative correlations were represented in red.

A principal component analysis (PCA) was also employed. This type of analysis is a powerful tool used to reduce the dimensionality of a data set of correlated variables while retaining most of its variability, by linearly combining these variables into principal components (Basha et al., 2018).

The analyses were performed in R software version 3.6.1 (R Core Team, 2019). The correlation network was generated from the Qgraph package (Epskamp et al., 2012). For principal component analysis, the FactoMineR package (Factor Analysis and Data Mining with R) was used (Lê et al., 2008)

Results

The use of the different artificial diets promoted good results, and some of these materials present high potential as an alternative to the use of carrots as the basis for the diet of *C. capitata* in the laboratory.

The artificial diet based on raw cassava was not viable, because it did not allow the hatching of *C. capitata* larvae. There were no differences among treatments for number of pupae (NP), pupal width (PWI), and pupal weight (PWE) except for yam (raw)(Table 2). For pupal length (PL), the diets based on sweet potato and pumpkin (raw and cooked) were superior to the other treatments, including the control.

Table 2. Number of pupae (NP), pupal length (PL), pupal width (PWI), and pupal weight (PWE) of *Ceratitis capitata* maintained on different artificial diets.

Artificial Diet	NP ^a	PL ^b	PWI ^a	PWE ^a
Raw sweet potato	46.9 ± 0.99 a	4.961 ± 0.05 a	2.066 ± 0.03 a	0.0117 ± 0.00010 a
Cooked sweet potato	46.5 ± 0.89 a	4.775 ± 0.05 b	2.025 ± 0.03 a	0.0113 ± 0.00016 a
Raw yam	17.1 ± 0.90 b	4.07 ± 0.07 d	1.925 ± 0.04 b	0.0071 ± 0.00020 b
Cooked yam	46 ± 0.51 ab	4.431 ± 0.03 c	2.06 ± 0.02 ab	0.0096 ± 0.00015 ab
Raw carrot	47.2 ± 0.71 a	4.661 ± 0.09 b	2.021 ± 0.03 a	0.0113 ± 0.00022 a
Cooked carrot	47.1 ± 0.75 a	4.666 ± 0.05 b	2.056 ± 0.01 a	0.012 ± 0.00019 a
Raw pumpkin	48.1 ± 0.52 a	5.02 ± 0.02 a	2.094 ± 0.02 a	0.0131 ± 0.00028 a
Cooked pumpkin	44.9 ± 1.26 ab	4.884 ± 0.04 a	2.034 ± 0.03 ab	0.0116 ± 0.00031 ab
Cooked cassava	46.1 ± 1.1 a	4.448 ± 0.07 c	2 ± 0.02 a	0.0127 ± 0.00082 a
CV (%)	6.46	4.11	4.94	9.74

Means (± Standard Error) followed by the same letter in the column do not differ by (a) Dunn and (b) Scott-Knott tests (P <0.05).

There was a significant difference ($p < 0.001$) in the characteristics larval viability (LV), pupal viability (PV), and egg-adult viability (EAV), with lower averages observed in the treatment with raw yam, which demonstrates the low potential for use as an artificial diet for *C. capitata*. On the other hand, when submitted to the cooking process, the yam presents improvements, especially for LV, being statistically equal to the best diets. It is also noteworthy the recurrence of this behavior for cooked cassava.

It was observed that *C. capitata* larvae fed with an artificial diet based on yam showed delayed development, low oviposition time, and low adult longevity when compared to the control (Table 4). On the other hand, insects fed with pumpkin and sweet potato (both raw and cooked) were statistically equal to the control.

Table 3. Larval viability (LV), pupal viability (PV), and egg-adult viability (EAV) of *Ceratitis capitata* were maintained on different artificial diets.

Artificial Diet	LV(%) ^a	PV (%) ^b	EAV(%) ^b
Raw sweet potato	93.8 ± 1.98 a	67.45 ± 3.43 b	63 ± 2.98 b
Cooked sweet potato	93 ± 1.79 a	81.79 ± 3.13 a	76.4 ± 3.90 a
Raw yam	34.2 ± 1.8 b	73.16 ± 5.86 b	24.8 ± 2.04 b
Cooked yam	92 ± 1.03 ab	65.73 ± 4.62 b	60.6 ± 4.41 b
Raw carrot	94.4 ± 1.42 a	80.18 ± 3.39 a	75.8 ± 3.66 a
Cooked carrot	94.2 ± 1.50 a	71.68 ± 2.23 b	67.6 ± 2.69 b
Raw pumpkin	96.2 ± 1.05 a	78.62 ± 4.17 a	75.6 ± 4.08 a
Cooked pumpkin	89.8 ± 2.53 ab	81.87 ± 4.61 a	73.2 ± 4.14 a
Cooked cassava	92.2 ± 2.2 a	77.26 ± 2.03 a	71.2 ± 2.48 a
CV (%)	6.46	16.37	16.78

Means (± standard error) followed by the same letter in the column do not differ by (a) Dunn and (b) Scott-Knott tests (P <0.05).

Table 4. Egg-to-adult time (EAT), pre-oviposition time (POT), oviposition time (OT), and adult lifetime (ALT) of *Ceratitis capitata* maintained on different artificial diets.

Artificial Diet	EAT	POT	OT	ALT
Raw sweet potato	16 ± 0.0 a	3 ± 0.0 a	9.7 ± 0.15 ab	31.1 ± 1.04 ab
Cooked sweet potato	16 ± 0.0 a	3 ± 0.0 a	11.4 ± 0.16 a	34.3 ± 0.36 a
Raw yam	18.5 ± 0.13 b	5 ± 0.39 b	3.5 ± 0.83 d	10.9 ± 1.35 d
Cooked yam	17.2 ± 0.16 b	2.9 ± 0.17 a	7.8 ± 0.55 c	19.1 ± 2.32 c
Raw carrot	16 ± 0.0 a	3 ± 0.0 a	10.3 ± 0.42 ab	27.3 ± 1.63 b
Cooked carrot	16 ± 0.0 a	3 ± 0.0 a	10.4 ± 0.16 ab	33.8 ± 0.29 a
Raw pumpkin	16 ± 0.0 a	3 ± 0.0 a	10.8 ± 0.13 a	29 ± 1.96 ab
Cooked pumpkin	16 ± 0.0 a	3 ± 0.0 a	11.4 ± 0.16 a	34.4 ± 0.4 a
Cooked cassava	17.9 ± 0.10 b	2.7 ± 0.21 a	9 ± 0.21 bc	30.9 ± 1.57 ab
CV (%)	1.49	16.03	13.05	15.91

Means (± standard error) followed by the same letter in the column do not differ by Dunn's test (P <0.05).

For sex ratio (SR), artificial diets based on raw and cooked pumpkin provided greater emergence of female insects (Table 5), a desirable characteristic, since they are responsible for egg oviposition and perpetuation of the species. For this variable, the diet based on yam proved to be very efficient; however, the females fed with this

base had low fecundity and eggs with low fertility.

It was also observed that the use of carrot-based diets led to low fecundity values, coupled with low fertility (<55%), and the diet obtained the lowest yield when compared to other bases, such as those derived from sweet potato and pumpkin.

Table 5. Sex ratio (SR), fecundity (Fec), and fertility (Fert) of *Ceratitis capitata* kept on different artificial diets.

Artificial Diet	RS	Fec	Fert (%)
Raw sweet potato	0.50 ± 0.01 b	106.57 ± 5.15 c	72.22 ± 1.31 a
Cooked sweet potato	0.52 ± 0.01 b	102.21 ± 4.43 c	74.44 ± 2.48 a
Raw yam	0.57 ± 0.02 a	13 ± 1.03 f	48.89 ± 1.79 b
Cooked yam	0.52 ± 0.01 b	52.37 ± 2.21 e	66.67 ± 2.26 ab
Raw carrot	0.51 ± 0.02 b	103.2 ± 3.92 c	54.44 ± 3.25 b
Cooked carrot	0.53 ± 0.02 b	113.22 ± 5.14 b	55.56 ± 1.98 b
Raw pumpkin	0.58 ± 0.02 a	96.95 ± 2.88 d	75.57 ± 0.99 a
Cooked pumpkin	0.59 ± 0.02 a	131.1 ± 7.25 a	73.33 ± 2.26 a
Cooked cassava	0.53 ± 0.03 b	106.87 ± 3.43 c	64.44 ± 0.50 ab
CV (%)	13.49	13.91	9.89

Means (± standard error) followed by the same letter in the column do not differ by Dunn's test (P <0.05).

The correlation matrix showed significant correlations between biometric and biological variables of *C. capitata* (Table 6), especially for pupal characteristics. However, variables such as SR and PV were neither

influenced nor had the potential to influence the other variables.

Table 6. Pearson's correlations between pupal biometry and biological characteristics of *Ceratitis capitata* adults maintained on different artificial diets.

VAR ^{1/}	SR	PV	Fec	Fert	PL	PWI	PWE	POT	OT	ALT
SR		0.37 ^{ns}	-0.09 ^{ns}	0.15 ^{ns}	0.03 ^{ns}	-0.12 ^{ns}	-0.08 ^{ns}	0.35 ^{ns}	-0.11 ^{ns}	-0.14 ^{ns}
PV			0.44 ^{ns}	0.2 ^{ns}	0.28 ^{ns}	-0.14 ^{ns}	0.34 ^{ns}	-0.1 ^{ns}	0.47 ^{ns}	0.43 ^{ns}
Fec				0.51 ^{ns}	0.79*	0.57 ^{ns}	0.88**	-0.78*	0.92**	0.97**
Fert					0.76*	0.65 ^{ns}	0.57 ^{ns}	-0.59 ^{ns}	0.64 ^{ns}	0.57 ^{ns}
PL						0.81**	0.77*	-0.65 ^{ns}	0.87**	0.78*
PWI							0.71*	-0.77*	0.72*	0.57 ^{ns}
PWE								-0.83**	0.85**	0.86**
POT									-0.83**	-0.76*
OT										0.93**

^{ns} Not Significant - * Significant at 5% level; ** Significant at 1% level by t test. ^{1/} Sex ratio (SR), Pupal Viability (PV), Fecundity (Fec), Fertility (Fert), Pupal Length (PL), Pupal Width (PWI), Pupal Weight (PWE), Pre-Oviposition Time (POT), Oviposition Time (OT), and Adult Lifetime (ALT).

The correlation network generated using the Fruchterman-Reingold algorithm (Figure 1) showed that pupae with greater length generate adults with greater longevity (ALT) ($r = 0.78$), females with longer oviposition

period ($r = 0.87$), greater fecundity (Fec) ($r = 0.79$) and greater fertility ($r = 0.76$). The best results for this variable were obtained with raw and cooked pumpkin and raw sweet potato.

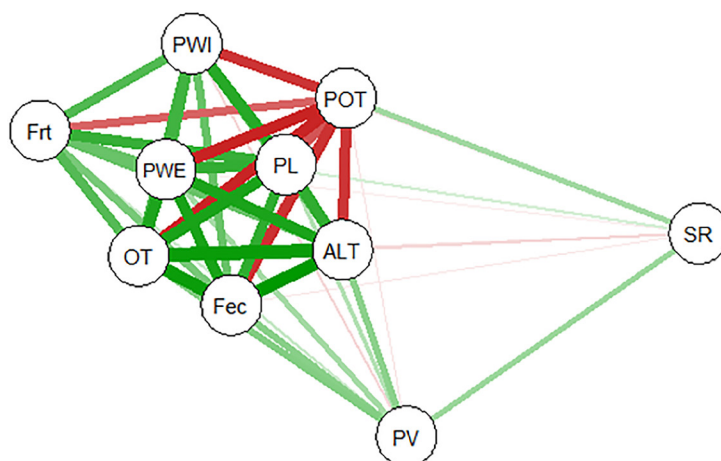


Figure 1. Network of correlations between pupal biometry and biological characteristics of *Ceratitis capitata* adults maintained on different artificial diets. Red lines represent negative correlations and green positive ones. The thickness of the line is proportional to the magnitude of the correlation. Sex ratio (SR), Pupal Viability (PV), Fecundity (Fec), Fertility (Frt), Pupal Length (PL), Pupal Width (PWI), Pupal Weight (PWE), Pre-Oviposition Time (POT), Oviposition Time (OT), and Adult Lifetime (ALT).

There was also a correlation between pupal weight (PWE) with pre-oviposition time (POT) and fecundity (Fec) so that heavier pupae lead to the hatching of adults with a shorter pre-oviposition period (POT) ($r = -0.83$) and higher fecundity (Fec) ($r = 0.88$). Regarding the biological characteristics, it was observed that insects that reached a shorter pre-oviposition period (POT) had a longer lifetime (ALT) ($r = -0.76$) and higher fecundity (Fec) ($r = -0.78$).

The principal component analysis (PCA) explained 81.8% of the original variance of the data in the first two axes (CP1 and CP2)(Figure 2). In axis 1, which accounted for 69.5% of the data explanation, we observed significant antagonistic behavior ($p < 0.001$) between OT ($r = 0.97$), EAV ($r = 0.95$), NP ($r = 0.95$), LV ($r =$

$r = 0.95$), Fec ($r = 0.90$), PWE ($r = 0.90$), ALT ($r = 0.90$), PL ($r = 0.88$), PWI ($r = 0.81$) and Fert ($r = 0.69$) with the POT ($r = -0.90$) and EAT ($r = -0.83$). Evidencing that longer egg-adult and pre-oviposition periods imply a reduction in several aspects, especially biological ones, such as oviposition time, fecundity, and fertility.

For this axis, we observed a distinct behavior among treatments, as well as the formation of two clusters; one formed by the raw yam, which showed the highest values of POT and EAT; and another cluster formed by the other diets, which were characterized by the best metrics, especially pumpkin (raw and cooked).

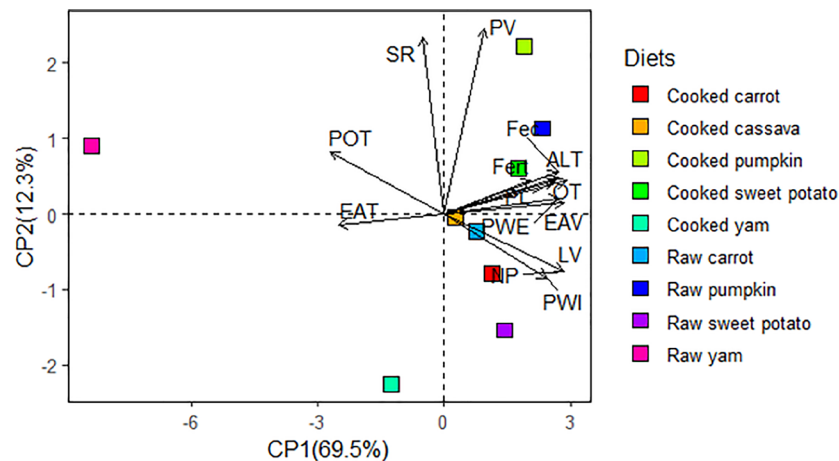


Figure 2. Principal Component Analysis (PCA) of biometric and biological characteristics of *Ceratitis capitata* kept on different artificial diets. Number of pupae (NP), Pupa Length (PL), Pupa Width (PWI), Pupa Weight (PWE), Larval Viability (LV), Pupa Viability (PV), Egg-Adult Viability (EAV), Egg-to-Adult Time (EAT), Pre-Oviposition Time (POT), Oviposition Time (OT), Adult Lifetime (ALT), Sex Ratio (SR), Fecundity (Fec) and Fertility (Fert).

In axis 2 in turn, with 12.3% of the original variance explanation, there was a significant association ($p < 0.001$) of PV ($r = 0.82$) with SR ($r = 0.78$). Indicating that treatments that provide higher pupal viability also led to a higher sex ratio and vice versa. For this axis, the diet based on cooked yam stands out, which showed the lowest values of pupal viability and low sex ratio.

The PCA, in summary, showed the low potential of using an artificial diet based on yam, either raw or cooked, as the basis for the diet of *C. capitata* under laboratory conditions. At the same time, it demonstrates that the use of other sources, such as pumpkin and sweet potato, can replace carrots, with satisfactory results.

Discussion

The results of this study reinforce that *Ceratitis capitata* reared under laboratory conditions exhibit the ability to develop amid a wide range of fluctuations in the nutritional environment. This plasticity may tampon the adult phenotype against the effects of environmental variation during larval development (Nash & Chapman, 2014). However, as seen here, this plasticity was not verified in some biological characteristics, such as the lifespan and fecundity of adults from diets derived from raw and cooked yam. Under laboratory conditions, the biology of the insect is strictly linked to its feeding, assimilation, and absorption of nutrients (Zahran et al., 2018; Moadeli et al., 2020).

The diet used as a larval substrate is an experimental parameter that usually varies in fruit fly growth and development experiments, and the nutritional quality of this material affects the development time and survival of these pest insects (Hamby et al., 2016). This can

even inhibit larval hatching (Dias et al., 2019), as observed here for the raw cassava-based diet.

The inhibition of hatching of *C. capitata* larvae in the raw cassava-based diet is possibly due to the presence of antinutritional factors in this root, such as variable contents of cyanogenic glycosides (Kasankala et al., 2019). The low values of larval viability (LV) observed in the raw yam diet can also be linked to the presence of different harmful substances in this tuber, which include phenol, tannin, oxalate, phytate, and alkaloids (Abiodun & Akinoso, 2014).

However, unlike what was observed in the raw diets, when cooked, yam and cassava become a more favorable environment for the development of *C. capitata*, although most of the time with lower results than the other diets. Home cooking methods affect the nutritional values of foods, so this step can considerably reduce the presence of antinutritional factors in foods (Ezeocha & Ojmelukwe, 2012; Zhao et al., 2019) and allow the availability of some beneficial nutrients (Zhao et al., 2019).

Proteins and carbohydrates are the main nutritional constituents present in artificial diets that contribute to fruit fly development (Nash & Chapman, 2014; Hou et al., 2020). The food bases used in this study have different nutritional values. Carrot, for example, has about 0.8% protein and 8.9% carbohydrates; while yam, sweet potato, and cassava have approximately 2%, 1.3%, and 1% protein, respectively; and 24.3%, 28.6%, and 32.8% carbohydrates, respectively (Daron et al., 2020). Pumpkin, on the other hand, has about 1.1% protein and 3.1% carbohydrates (Junqueira et al., 2017).

The results obtained here show that the use of

dietary bases rich in protein and carbohydrates, such as yam, does not necessarily reflect positively on the larval development and biological aspects of *C. capitata*. It is noteworthy that all diets used had yeast in its composition, a material with a high proportion of protein (Hou et al., 2020). Thus, yam-derived diets may have been left with high levels of this nutrient, and although proteins are essential for the development of Diptera, high concentrations can generate harmful effects, for example, body development (Sentinella et al., 2013).

The absorption of nutrients during larval feeding promotes not only immediate growth, but also the accumulation of resources that will later be used by the pupa and adult (Leftwich et al., 2016). Artificial diets, besides proteins and carbohydrates, have many other components, some of which, even if present in small amounts, are essential for the development of Diptera (Sentinella et al. 2013). Pumpkin, for example, is well known as an important source of carotenoids, vitamins, and minerals (Junqueira et al., 2017), as are sweet potatoes and carrots (Daron et al., 2020), constituents that can significantly enhance larval and adult development of fruit flies (Zahran et al., 2018).

Although females of *C. capitata* are anautogenous, the nutritional reserves absorbed and transported from the larval stage may provide a distinct reproductive advantage; influencing, for example, a higher production of viable eggs (Kaspi et al., 2002), which in this study can be observed for the fertility of eggs from females fed in the larval period with diets based on sweet potato and pumpkin. In this same sense, when inoculated in a nutrient-poor environment, larvae may adaptively shorten their development period (Kaspi et al., 2002).

The diets based on cooked yam and cassava had a more viscous and solid aspect. This may have led the larvae to demand more effort to perforate these substrates, seeking to optimize abiotic factors, such as greater humidity and darkness, than to consume the diet (Schwarz et al., 2014). It is also noteworthy that the moisture of the diet influences the larval development of Diptera, with negative responses of these insects to diets with low water content (Cammack & Tomberlin, 2017).

The positive correlations between pupal biometrics, notably weight and length, with biological aspects such as fertility, fecundity, and longevity reinforce the premise that heavier pupae are extremely desirable in mass rearing of fruit flies based on artificial diets since these lead to higher performing adult insects (Sookar et al., 2014).

In this same sense, obtaining fruit flies with shorter pre-oviposition time indicates that the artificial diet used provided the generation of well-nourished adults suitable for mating. This is also reflected in greater longevity, and consequently, greater fecundity. It is noteworthy that quantitative and qualitative variations in diet nutrients significantly influence the timing of the main developmental events of *C. capitata* (Leftwich et al., 2016).

The Principal Component Analysis (PCA) demonstrated the negative association between biological aspects, such as oviposition time, fecundity, and fertility, with the longer egg-adult and pre-oviposition periods in *C. capitata*. Results show that fruit flies with slow development, such as those obtained from the diet based on raw yam, have reproductive disadvantages compared to others with normal or early development, such as those obtained from diets based on the carrot, pumpkin, sweet potato, and cooked cassava. At the same time, it shows that even after undergoing the cooking process, the yam leads to pupae with low viability and adults with a lower sex ratio. Our results together allow us to indicate the non-use of yam (raw or cooked) as a basis for artificial diets for *C. capitata*, in addition to demonstrating the influence of antinutritional factors on the development of this important pest.

Sweet potato and pumpkin were shown to have a high potential to replace carrot in artificial diets, generating a favorable environment for larval development and the generation of *C. capitata* adults with good fecundity and fertility, an indispensable condition for the good progress of mass rearing (González-López et al., 2019).

One of the disadvantages of artificial solid diets, such as those used in this study, is the risk of contamination by pesticides of the food bases used (Hou et al., 2020), leading to mortality or low viability of mass rearing. This situation is recurrent with carrot-based diets, whose production in Brazil makes great use of these inputs. Thus, the use of materials such as sweet potato and pumpkin, which in the Northeast of Brazil are usually produced by small producers with the absence or low use of pesticides, becomes a strategy for the production of a low-cost, efficient, and safe artificial diet.

Conclusions

Artificial diets derived from pumpkin and sweet potato (both raw and cooked) were superior to the diet control (carrot) in the growth and development of *C. capitata* and may be recommended for this purpose.

The raw materials yam (raw and cooked) and

cassava (raw) should not be used in the artificial diet of this species.

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