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Growth and Development of *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae) Fed on Artificial Diets Enriched with Wild Host Plants

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ABSTRACT

The quality of artificial diets is important to produce high quality cultures of *S. frugiperda*. The research aimed to determine the effect of artificial diets based on wild plants on the growth and development of *Spodoptera frugiperda*. The plants used for enriching artificial diets were *Zea mays* (control), *Ipomoea aquatic*, *Ipomoea reptans*, *Amaranthus hybridus*, *Morus rubra*, *Brachiaria mutica*, and *Setaria sphacelata*. The results showed that *S. frugiperda* larvae consuming artificial diets enriched with *A. hybridus*, *Z. mays*, *I. reptans*, and *I. aquatic* leaves had higher body weight, lower larval mortality and abnormal pupae compared to those of *B. mutica*, *S. sphacelata* and *M. rubra* leaves. The adult females from larvae-consuming diets enriched with *A. hybridus, Z. mays, I. reptans, I. aquatica*, and *S. sphacelata* leaves had higher fecundity compared to those of other diets. However, diet enriched with *S. sphacelata* leaves caused higher larval mortality. Thus, the more suitable diets to increase the larval growth and survival, and adult emergence and fecundity were the diets enriched with wild host plants (*A. hybridus*, *I. reptans*, and *I. aquatic* leaves). Using weed or wild host plant leaves to produce artificial diets is feasible for mass-rearing *S. frugiperda.*

INTRODUCTION

Fall armyworm, *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae) is a new pest in Indonesia. The pest is originated from from South America (Otim et al. 2018) and enter to Indonesia in March 2019 (Sartiami et al. 2020). *S. frugiperda* is a destructive and polyphagous insect (Silva et al., 2017). In 2020, its distribution reached maize production centers throughout Indonesia (Russianzi et al., 2021), such as South Sumatra (Herlinda et al., 2020; Hutasoit et al., 2020), Bengkulu (Ginting et al., 2020), and Bali (Saleh et al., 2023; Supartha et al., 2021). It attacks of various host plants from different families, namely 353 species from 76 families, especially Poaceae, Asteraceae, and Fabaceae (Montezano et al., 2018). Two strains of *S. frugiperda* have been found in Indonesia, the rice and maize strains, threatening the sustainability of maize and rice (*Oryza sativa* L.) (Herlinda et al., 2022c). The damage to maize caused by this pest reaches 100% in Lampung (Lestari et al., 2020), East Nusa Tenggara (Mukkun et al., 2021), Bali (Supartha et al., 2021), and South Sumatra (Herlinda et al., 2022c). Approximately US$13 million in annual financial losses due to *S. frugiperda* infestation (Harrison et al., 2019). There are 28 plant species that have the potential to become hosts for *S. frugiperda* (Herlinda et al., 2022b). They include maize, cotton (*Gossypium hirsutum* L.), buckwheat (*Sorghum bicolor* L.) (Dumas et al., 2015), soybean (*Glycine max* (L.) Merr.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.) (Silva et al., 2017), land

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spinach (*Ipomoea reptans* Poir), white mulberry (*Morus alba* L.), water spinach (*Ipomoea aquatica* Forsk), pigweed (*Amaranthus hybridus* L.), para grass (*Brachiaria mutica* Forsk. Stapf.), setaria (*Setaria sphacelata* (Nandi)) (Herlinda et al., 2022b).

Many studies have been carried out to address the problem of *S. frugiperda*, including studies on its biology, growth and development (Navasero et al., 2021), bioassay of entomopathogenic fungi against larvae of *S. frugiperda* (Herlinda et al., 2021, 2022a) or insecticide toxicology against larvae of *S. frugiperda* (Silva et al., 2016), and control using sterile insects (Sayed et al., 2021). These studies require large numbers of test insects, and the insects are expensive if they test insects are mass-reared on their natural host plants (Di Bello et al., 2017). Therefore, artificial diets for mass-rearing test insects are required for effectiveness and efficiency in basic and applied research on *S. frugiperda* (Ashok et al., 2021).

Many artificial diets have been used for the mass rearing of *S. frugiperda*, including those based on maize leaves, castor beans, cotton (Ramos et al., 2022) and rice leaves (Ashok et al., 2021). Artificial diets must consider the quality and cost of making them; for example, artificial diets made from wheat bran are cheaper than those made from soybeans or yeast flour (Ge et al., 2022). However, an artificial diet made from the highest quality soy ingredients is suitable for developing the *S. frugiperda* but more expensive (Thamrin et al., 2022). The quality of the artificial diet consumed by host insects for entomopathogenic viruses can also influence the influence the virus's pathogenicity and the production of sterile insects (Sayed et al., 2021). Artificial diets containing bactericides can reduce the pathogenicity of entomopathogenic bacteria (Aggarwal et al., 2014).

Therefore, cheap but high-quality artificial diets need to be continuously developed. Host plants that are easy to grow in the field (Javar et al., 2013), colors and flavors have a high nutritional value, and colors and flavors are potential to be used as a dietary source for insect mass-rearing (Villegas-Mendoza & Rosas-García, 2013). Previous research showed that several host plant species, such as land spinach, white mulberry, water spinach, pigweed, para grass and setaria, are preferred and consumed by *S. frugiperda* (Herlinda et al., 2022b). These wild host plant species are able to grow well without the need for cultivation and management in the field. They have never been used as essential ingredients in the production of artificial diets for *S. frugiperda*. In contrast, the artificial diets available on the market are relatively expensive and the quality cannot be determined for sustainable mass rearing of *S. frugiperda*. These wild plant species can be used as essential ingredients in producing artificial diets for *S. frugiperda*, resulting in good quality *S. frugiperda* cultures that are sustainably available. From present research, high-quality artificial diets can be found from wild plant ingredients to produce high-quality *S. frugiperda* cultures. This culture creates a lot of offspring and a high survival rate, and its quality is equivalent to a culture made from maize leaves. The research aimed to determine the effect of artificial diets based on wild plants on the growth and development of *S. frugiperda*.

MATERIALS AND METHODS

Preparation of Test Insects, *Spodoptera frugiperda*

The research was conducted in April up to August 2023. Eggs and larvae of the test insect (*S. frugiperda*) were collected from maize fields in Indralaya (3°1′12″S, 104°28′48″E), South Sumatra. Eggs and larvae were brought to the Entomology Laboratory, Department of Plant Protection, Faculty of Agriculture, Universitas Sriwijaya. *S. frugiperda* was identified molecularly (Herlinda et al., 2022c), and its eggs and larvae were reared according to the method of Herlinda et al. (2021) and the larvae were fed with corn leaves and individually placed in a plastic cup (Ø = 60 mm and height = 40 mm). Larvae that develop into prepupae and pupae were transferred into a wire mesh cage (50 × 50 × 50 cm), which had been provided with a container containing 3 cm thickness of powdered soil. The soil was sterilized in an oven at 100°C for 40 minutes (Gustianingtyas et al., 2021). A young maize plant was also in the cage for the adults to lay their eggs. The mass-rearing room was controlled in the light period of 12 hours and the dark period of 12 hours (Pinto et al., 2019).

Artificial Diet Preparation

Artificial diets had been developed by modifying methods of Sreelakshmi & Mathew (2017) and Jin et al. (2020). The plant leaves used for each treatment were different and each of the seven treatments contained 50 g of crushed leaves: a) maize (*Zea mays* L.) (control), b) water spinach (*I.*

aquatic), c) land spinach (*I. reptans*), d) pigweed (*A. hybridus*), e) red mulberry (*Morus rubra* L.), f) para grass (*B. mutica*), and g) setaria (*S. sphacelata*) (Table 1). For other ingredients, all treatments contain Fraction-A (water, yeast, corn flour, methyl-p-hydroxybenzoate, sorbic acid, jelly), Fraction-B (multivitamin, ascorbic acid), and Fraction-C (formaldehyde 10%) with the same composition. To increase the palatability of the diet for the insects, artificial diets were made by crushing the treated leaves first (Jin et al., 2020). The crushed leaves, distilled water, the corn flour were sterilized in oven with temperature of 120°C atm for 30 minutes. The other ingredients of Fraction A (yeast, methyl-p-hydroxybenzoate, sorbic acid, jelly) and the crushed leaves, distilled water, and maize flour were mixed in a container (volume 350 ml) and then the mixture was ground using a blender for 10 minutes while adding lukewarm distilled water. The container containing Fraction A was put into a pressure cooker and boiled at 100°C with 1 atm pressure for 10 minutes. Then, the Fraction A was removed from the pressure cooker and allowed to cool down to a room temperature for about 2 minutes. The jelly of Fraction B was dissolved in hot distilled water (100°C) in a sterile plastic container (volume 350 ml) and completely mixed. The jelly was then cooled until 70°C and mixed with the Fraction A. The mixture was thoroughly mixed for about 2 minutes. Fraction C (1.5 ml of 10% Formaldehyde) was added to the mixture and thoroughly mixed for 1 minute at room temperature. The mixture of the Fractions A, B, and C was placed into a sterile plastic container and cooled in a refrigerator at 4°C. The hardened diet was cut into a piece of about 1 × 0.5 × 0.5 cm for feeding to the larvae.

Table 1. Composition of artificial diet for *Spodoptera frugiperda* larvae

Composition of artificial diet	**Artificial diets**						
	***Zea mays* (control)**	***Ipomoea reptans***	***Ipomoea aquatica***	***Amaranthus hybridus***	***Morus rubra***	***Brachiaria mutica***	***Setaria sphacelata***
Fraction-A							
Water (ml)	500	500	500	500	500	500	500
Yeast (g)	20	20	20	20	20	20	20
Corn flour (g)	150	150	150	150	150	150	150
Zea mays leaves (g)	50	-	-	-	-	-	-
Ipomoea reptans leaves (g)	-	50	-	-	-	-	-
Ipomoea aquatic leaves (g)	-	-	50	-	-	-	-
Amaranthus hybridus leaves (g)	-	-	-	50	-	-	-
Morus rubra leaves (g)	-	-	-	-	50	-	-
Brachiaria mutica leaves (g)	-	-	-	-	-	50	-
Setaria sphacelata leaves (g)	-	-	-	-	-	-	50
Methyl-p-hydroxybenzoate (g)	2	2	2	2	2	2	2
Sorbic acid (g)	1	1	1	1	1	1	1
Jelly (g)	10	10	10	10	10	10	10
Fraction-B							
Multivitamins (g)	1	1	1	1	1	1	1
Ascorbic acid (g)	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Fraction-C							
Formaldehyde 10% (ml)	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Bioassay of the Effect of Artificial Diet on the Growth and Development of *Spodoptera frugiperda*

The artificial diet (1 × 0.5 × 0.5 cm) was maintained at room temperature for 2 hours (Jat et al., 2020) before being offered to the first instar larvae (neonate) of *S. frugiperda*. Thirty individuals of the first larvae (hatching within 24 hours) were put into plastic cups (ø = 6 cm and height = 4 cm) with five repetitions. Each cup was filled with three an artificial diet measuring 1×1×1 cm (Ashouri et al., 2022) and replaced at 3-day intervals until the first larvae molting. To prevent cannibalism after the larvae become the second instar (approximately three days), they were moved individually in separate plastic cups until they became pupae. The number of surviving larvae and body weight of larvae were recorded.

Developmental time of *S. frugiperda* larvae, prepupae and pupae, adult longevity, fecundity (number of eggs), fertility (eggs hatched), and the percentage of adult emergence were recorded. Five pairs of newly emerged adults from the same diet treatment were selected and transferred to a transparent plastic container (ø = 16 cm and height = 50 cm) with an air-permeable lid. The cage was equipped with maize leaves as a place for the adults to lay eggs (Sari et al., 2022) and contained 10% cotton soaked in honey in a bottle cap for feeding the adults. The percentage of eggs that hatched (fertility) was also recorded at 24-hour intervals. Each treatment had five replications.

Nutritional Indices

The method of Pinto et al. (2019) observation of nutritional indices was carried out by determining the quantitative nutritional index of the fourth instar. Thirty individuals of the newly hatched larvae (neonate larvae) that had been treated with an artificial diet, and the diet was changed every three days. When the larvae ten reached the fourth instar stage, ten larvae were removed from a plastic container (Ø 6 cm height by 4 cm), weighed, killed by freezing in the freezer, and dried in the oven. The other ten larvae were weighed and left in a plastic container containing the artificial diet to continue their life. When the larvae reached the fifth instar, characterized by the presence of larval exuviae in a plastic container, the same procedure described above was carried out, namely weighing, killing by freezing in a freezer, and drying in an oven. Additionally, the remaining diet and feces from insects during the fourth instar and the intact artificial diet from each container were weighed and oven-dried. Diet, feces, and larvae were oven-dried for three days until they reached constant weight and then weighed. Next, T = duration of the consumption period (days); Af = weight of diet given to larvae (g); Ar = weight of remaining diet (g) after T; F = weight of excretion (feces) produced by larvae (g) during T; B= (I – F) – M: increase in larval weight (g) during T; B = average weight of larvae (g) during T; I = weight of diet consumed (g) during T; I–F: assimilated diet (g) during T; M: (I – F) – B: diet metabolized during T (g). The food consumption and use index was determined using the following equation:

Relative consumption rate (g/g/day) = RCR = $\frac{I}{B \times T}$ ...1)

Relative growth rate (g/g/day) = RGR = $\frac{B}{B \times T}$ ....2)

Relative metabolic rate (g/g/day) = RMR = $\frac{M}{B \times T}$ ..3)

Proximate digestibility (%) = AD = $\frac{I - F}{I} \times 100$ ......4)

The efficiency of conversion of ingested food (%) = ECI = $\frac{B}{T} \times 100$ ....5)

The efficiency of conversion f digested food (%) = ECD = $\frac{B}{I - F} \times 100$ ....6)

Metabolic cost (%) = CM = 100 – ECD ....7)

Data Analysis

To determine the effect of giving an artificial diet on the growth and development of *S. frugiperda*, the data differences in each treatment were analyzed using analysis of variance (ANOVA) in R 4.1.2 software. Mean comparison was perfomed using Honest Significant Difference (HSD) test at the 5% level.

RESULTS AND DISCUSSION

Growth of *S. frugiperda* Fed on Artificial Diets Enriched with Wild Host Plants

The body weight of *S. frugiperda* first-instar larvae after consuming artificial diets enriched with *A. hybridus* leaves was the highest among other treatments ($p < 0.0001$) but not significantly different from those of the diets enriched with *Z. mays*, *I. reptans*, *I. aquatica*, and *S. sphacelate* leaves (Table 2). The body weight of the following instar larvae (the second up to sixth-instar larvae) consuming artificial diets enriched with *A. hybridus* leaves was the highest and significantly different from those of other treatments (p < 0.0001). Fresh and dried weight of *S. frugiperda* larvae after consuming artificial diets enriched with *A. hybridus* leaves was also the highest ones (Fig. 1). Thus, the artificial diets enriched with *A. hybridus* leaves was the best diet to increase the body weight of *S. frugiperda* larvae.

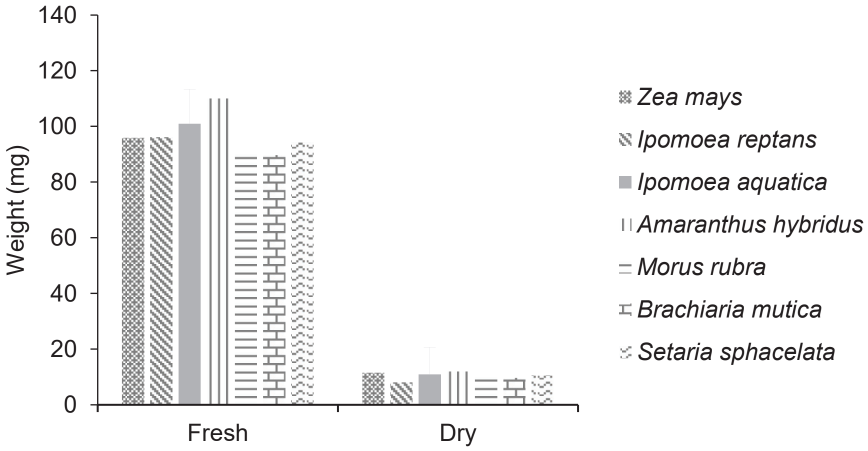

Fig. 1. Fresh and dried weight of *Spodoptera frugiperda* larvae after consuming artificial diets.

Table 2. Body weight of *Spodoptera frugiperda* larvae after consuming artificial diets.

Artificial diets	Mean of larval body weight (mg)					
	1st instar	**2nd instar**	**3rd instar**	**4th instar**	**5th instar**	**6th instar**
Zea mays	7.87±0.16a	18.13±0.21bc	41.90±0.77bc	97.77±0.73bc	134.64±0.96bc	190.51±1.34bc
Ipomoea reptans	7.62±0.18abc	18.01±0.11bc	42.85±0.68bc	98.10±0.94bc	134.75±1.14bc	190.00±1.50bc
Ipomoea aquatica	8.14±0.18a	18.74±0.62b	43.94±0.59b	100.96±0.43b	138.98±0.58b	196.01±0.89b
Amaranthus hybridus	8.29±0.08a	21.44±0.25a	51.51±0.81a	111.53±0.89a	152.56±0.98a	212.58±1.10a
Morus rubra	7.05±0.12c	17.34±0.34bc	37.41±0.65d	90.86±0.84d	125.30±1.15d	178.75±1.49d
Brachiaria mutica	7.12±0.10bc	16.55±0.32c	36.33±0.31d	89.13±0.74d	124.72±0.61d	177.51±0.52d
Setaria sphacelata	7.73±0.08ab	17.14±0.51bc	40.36±0.55c	94.96±0.69c	130.57±1.12c	185.17±1.63c
F-value	9.74**	13.20**	47.58**	70.65**	73.33**	66.84**
p-value	8.16×10^{-6}	4.71×10^{-7}	2.08×10^{-13}	1.31×10^{-15}	8.05×10^{-16}	2.69×10^{-15}
HSD value	0.04	0.05	0.03	0.02	0.02	0.01

Remarks: * means significant difference; values within a column with the same letters were not significantly different at P < 0.05 according to Tukey’s HSD test; original data were transformed using the square root before statistical analysis.

Table 3. Nutritional indices of *Spodoptera frugiperda* larvae after consuming artificial diets.

Nutritional indices	Artificial diets							F-value	p-value	HSD value
	Zea mays	***Ipomoea reptans***	***Ipomoea aquatica***	***Amaranthus hybridus***	***Morus rubra***	***Brachiaria mutica***	***Setaria sphacelata***			
RCR (g/g/day)[a)]	2.07±0.12b	2.15±0.07b	2.52±0.05ab	2.35±0.16b	2.01±0.09b	3.45±0.39a	2.01±0.16b	6.65*	1.86×10^{-4}	0.24
RGR (g/g/day)[a)]	0.10±0.00ab	0.09±0.00abc	0.09±0.00abc	0.11±0.01a	0.09±0.00bc	0.08±0.01c	0.09±0.00bc	5.22*	1.02×10^{-3}	0.01
RMR (g/g/day)[a)]	0.18±0.03c	0.08±0.01de	0.24±0.01b	0.26±0.02b	0.11±0.01d	0.37±0.02a	0.05±0.01e	33.35*	1.66×10^{-11}	0.03
AD (%)[b)]	44.57±2.73bc	28.62±1.38d	48.44±0.95ab	48.40±2.03b	36.88±1.48c	57.79±0.66a	26.97±1.19d	38.38*	3.00×10^{-12}	0.64
ECI (%)[b)]	16.40±0.95a	15.57±0.50a	13.26±0.28ab	14.48±0.97a	16.73±0.74a	10.24±1.04b	17.00±1.14a	6.68*	1.80×10^{-4}	0.56
ECD (%)[b)]	38.14±4.51bcd	55.43±4.21ab	27.43±0.80de	30.36±2.98cde	45.89±3.16abc	17.83±1.98e	64.01±6.01a	17.84*	2.11×10^{-8}	1.38
CM (%)[b)]	61.86±4.51abc	44.57±4.21cd	72.57±0.80ab	69.64±2.98ab	54.11±3.16bc	82.17±1.98a	35.99±6.01d	12.89*	5.94×10^{-7}	1.39

Remarks: * means significant difference; ns means non-significant difference; values within a row with the same letters were not significantly different at $P < 0.05$ according to Tukey's HSD test; ; [a)]Original data were transformed using logarithmic transformation; [b)]original data were transformed using the Arcsin transformation before statistical analysis.

Concerning nutritional indices, the relative consumption rate (RCR) of larvae after consuming artificial diets enriched with *B. mutica* leaves was the highest among other treatments ($p < 0.0007$). However, it was not significantly different from those of artificial diets enriched with *I. aquatica* leaves (Table 3). The relative growth rate (RGR) of larvae after consuming artificial diets enriched with *A. hybridus* leaves was the highest ($p < 0.001$), but it was not significantly different from those of artificial diets enriched with *Z. mays*, *I. reptans*, *I. aquatic* leaves. The relative metabolic rate (RMR) of larvae after consuming artificial diets enriched with *B. mutica* leaves was the highest ($p < 0.0001$) and significantly different from other treatments. The approximate digestibility (AD) of larvae after consuming artificial diets enriched with *B. mutica* and *I. aquatica* leaves was significantly higher than those of other treatments ($p < 0.0001$). The efficiency of conversion of ingested food (ECI) of larvae after consuming artificial diets enriched with *B. mutica* and *I. aquatica* leaves was significantly lower ($p < 0.00018$) compared to other treatments. The efficiency of conversion of digested food (ECD) of larvae after consuming artificial diets enriched with *S. sphacelata*, *I. reptans*, and *M. alba* leaves was significantly higher than those of other treatments ($p < 0.0001$). The metabolic cost (CM) of larvae after consuming artificial diets enriched with *B. mutica*, *A. hybridus*, *I. aquatica*, and *Z. mays* leaves was significantly higher compared to other treatments ($p < 0.0001$).

Development of *Spodoptera frugiperda* Fed on Artificial Diets Enriched with Wild Host Plants

Developmental time of *S. frugiperda* first-instar larvae after consuming artificial diets enriched with *M. rubra* leaves was the longest one among other treatments ($p < 0.0001$) (Table 4). The longest developmental time of the second-instar larvae occured in diet enriched with *B. mutica* leaves and was significantly different ($p < 0.0001$) from other diets. Developmental time of third ($p < 0.0001$), fourth ($p < 0.0001$), fifth ($p < 0.0001$), and six-instar larvae ($p < 0.0001$) after consuming artificial diets enriched with *M. rubra* and *B. mutica* leaves was significantly higher compared to other diets. Thus, total of developmental time of *S. frugiperda* consuming artificial diets enriched with *M. rubra*, *S. sphacelata*, *B. mutica* leaves was significantly longer ($p < 0.0001$) compared to other diets (Table 5). Adult longevity of *S. frugiperda* was not influenced by the artificial diets.

Mean of percentage of larval mortality in artificial diets enriched with *B. mutica*, *S. sphacelata* and *A. hybridus* was significantly higher ($p < 0.0001$) than those of other diets (Table 6). Larvae-consuming diets enriched with *S. sphacelata*, *B. mutica*, and *M. rubra* could induce higher abnormal pupae compared to other diets. The highest percentage of pupal ($p < 0.0001$) and adult ($p < 0.0001$) emergences ocurred in artificial diets enriched with *I. aquatica*. However, it was not significantly different from those of artificial diets enriched with *I. reptans*, *Z. mays*, *A. hybridus*, and *M. rubra*. The sex ratio of *S. frugiperda* produced from larvae consuming artificial diets did not show a significant difference among treatments.

The artificial diets consumed by larvae significantly affected their adult fecundity (number of eggs) ($p < 0.0001$) and egg fertility (eggs hatched) ($p < 0.05$) (Table 7). The highest fecundity of *S. frugiperda* adults occurred in diets enriched with *A. hybridus* leaves, but it was not significantly different from those of diets enriched with *Z. mays*, *I. reptans*, *I. aquatica*, and *S. sphacelata* leaves. The lowest adult fecundity occurred in diets enriched with *B. mutica* leaves. All the treatments had more than 90% of egg fertility. The lowest egg fertility occurred in diets enriched with *M. rubra* leaves and was significantly different from the diet enriched with *Z. mays* but was not significantly different from other treatments. We also found malformed or deformed pupae from larvae consuming artificial diets enriched with *B. mutica* leaves (Fig. 2).

The diet enriched with *Z. mays* leaves was the control treatment because *Z. mays* leaves was the diet generally used for rearing *S. frugiperda* and it was the most preferred host in the fields. The current study was to replace the diet enriched with *Z. mays* leaves with a diet enriched with weed or wild host plant leaves. *S. frugiperda* first-instar larvae, after consuming artificial diets enriched with *A. hybridus* leaves, had the highest body weight, and also, the larvae consuming artificial diets enriched with *Z. mays*, *I. reptans*, *I. aquatica*, and *S. sphacelata* leaves had higher body weight. However, the next (older) instars consuming artificial diets enriched with *A. hybridus*, *Z. mays*, *I. reptans*, *I. aquatic* leaves had higher body weight than other diets.

Table 4. Developmental time of *Spodoptera frugiperda* larvae fed on artificial diets

Artificial diets	Mean of developmental time (days)					
	1st instar	2nd instar	3rd instar	4th instar	5th instar	6th instar
Zea mays	3.67±0.02c	3.81±0.07b	3.74±0.13abc	3.74±0.05c	3.76±0.07b	4.50±0.12b
Ipomoea reptans	3.42±0.01d	3.32±0.06c	3.06±0.19cd	3.27±0.06d	3.22±0.08c	3.48±0.14c
Ipomoea aquatica	3.43±0.02d	3.30±0.03c	3.34±0.17bcd	3.36±0.05d	3.33±0.07c	3.69±0.11c
Amaranthus hybridus	3.41±0.04d	3.29±0.07c	2.94±0.20d	3.21±0.05d	3.15±0.07c	3.36±0.12c
Morus rubra	4.52±0.03a	4.14±0.10b	4.00±0.07ab	4.22±0.05ab	4.12±0.06ab	5.35±0.10a
Brachiaria mutica	4.18±0.03b	4.91±0.09a	4.06±0.14ab	4.39±0.06a	4.45±0.09a	5.84±0.15a
Setaria sphacelata	4.06±0.06b	4.06±0.14b	4.14±0.10a	4.09±0.05b	4.10±0.06ab	5.19±0.11a
F-value	142.70**	38.77**	8.68**	69.88**	41.09**	51.36**
p-value	2.00×10^{-16}	2.65×10^{-12}	2.22×10^{-5}	1.51×10^{-15}	1.30×10^{-12}	7.89×10^{-14}
HSD value	0.04	0.10	0.19	0.06	0.09	0.14

Remarks: * means significant difference; values within a column with the same letters were not significantly different at P < 0.05 according to Tukey's HSD test; original data were transformed using the square root before statistical analysis.

Table 5. Developmental time of *Spodoptera frugiperda* prepupae and pupae and adult longevity from larvae fed on artificial diets

Artificial diets	Mean of developmental time (days)		Mean of adult longevity (days)	Total of developmental time (days)
	Prepupae	Pupae		
Zea mays	2.93±0.06bc	7.15±0.14d	7.26±0.19	40.54±0.44c
Ipomoea reptans	3.15±0.07ab	7.10±0.11d	7.39±0.19	37.40±0.37d
Ipomoea aquatica	3.08±0.06abc	7.07±0.07d	7.27±0.23	37.85±0.35d
Amaranthus hybridus	3.19±0.08ab	8.75±0.14bc	7.41±0.24	38.73±0.28cd
Morus rubra	3.30±0.04a	9.71±0.19a	7.87±0.39	47.23±0.59ab
Brachiaria mutica	2.80±0.08c	9.37±0.11ab	8.22±0.51	48.23±0.89a
Setaria sphacelata	2.97±0.06bc	8.24±0.15c	8.11±0.18	44.95±0.47b
F-value	5.80**	56.63**	1.48ns	66.12**
p-value	5.05×10^{-4}	2.28×10^{-14}	0.22	3.10×10^{-15}
HSD value	0.09	0.11	0.26	0.03

Remarks: * means significant difference; ns means non-significant difference; values within a column with the same letters were not significantly different at P < 0.05 according to Tukey's HSD test; original data were transformed using the square root before statistical analysis.

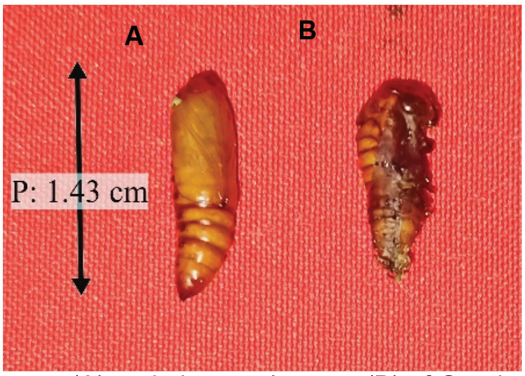

Fig. 2. Morphology of normal pupae (A) and abnormal pupae (B) of *Spodoptera frugiperda.*

Table 6. Mean of percentage of larval mortality, pupal emergence, adult emergence, and sex ratio of *Spodoptera frugiperda* fed on artificial diets.

Artificial diets	Mean of larval mortality (%)[a)]	Abnormal pupae (%)[a)]	Pupal emergence (%)[a)]	Adult emergence (%)[a)]	Sex ratio[b)]
Zea mays	7.20[bc]	0.80[c]	92.80[ab]	92.00[a]	0.95
Ipomoea reptans	5.20[c]	1.20[c]	94.80[a]	93.60[a]	1.05
Ipomoea aquatica	4.80[c]	1.20[c]	95.20[a]	94.00[a]	0.98
Amaranthus hybridus	8.00[abc]	2.80[bc]	92.00[abc]	89.20[a]	1.04
Morus rubra	5.60[c]	5.20[ab]	94.40[a]	89.20[a]	0.95
Brachiaria mutica	13.60[a]	11.60[a]	86.40[c]	74.80[b]	0.72
Setaria sphacelata	11.60[ab]	10.00[a]	88.40[bc]	78.40[b]	0.94
F-value	8.04*	14.36*	8.04*	25.73*	1.74[ns]
p-value	4.20×10^{-5}	2.04×10^{-7}	4.20×10^{-5}	3.57×10^{-10}	0.15
HSD value	5.37	8.03	5.37	5.59	-

Remarks: ns means not significant; * means significant difference; values within a column with the same letters are not significantly different at $P < 0.05$ according to Tukey's HSD test; a) original data were transformed using the Arcsin transformation; b)original data were transformed using the square root transformation before statistical analysis.

Table 7. Fecundity (number of eggs) and fertility (eggs hatched) of adults of *Spodoptera frugiperda* from larvae fed on artificial diets.

Artificial diets	Mean of fecundity (eggs/female)[a)]	Mean of egg fertility (%)[b)]
Zea mays	112.59±3.33[ab]	95.77±0.56[a]
Ipomoea reptans	109.92±4.54[ab]	93.48±0.78[ab]
Ipomoea aquatica	112.39±3.96[ab]	94.34±0.84[ab]
Amaranthus hybridus	120.38±1.45[a]	95.52±0.31[ab]
Morus rubra	81.07±4.04[c]	92.34±0.44[b]
Brachiaria mutica	98.71±1.55[b]	93.86±0.54[ab]
Setaria sphacelata	106.10±4.27[ab]	94.56±0.82[ab]
F-value	11.67**	2.62**
p-value	1.56×10^{-6}	0.04
HSD value	0.07	4.09

Remarks:* means significant difference; values within a column with the same letters are not significantly different at $P < 0.05$ according to Tukey's HSD test; [a)]Original data were transformed using logarithmic transformation; [b)]original data were transformed using the Arcsin transformation before statistical analysis.

In addition, larvae's relative growth rate (RGR) after consuming artificial diets enriched with *A. hybridus*, *Z. mays*, *I. reptans*, and *I. aquatic* leaves were higher than other diets. These data indicated that diets enriched with *A. hybridus* leaves had the same quality as diets enriched with *Z. mays*, *I. reptans*, and *I. aquatic* leaves. *A. hybridus*, *Z. mays*, *I. reptans*, *I. aquatic* leaves contained carbohydrates and protein that *S. frugiperda* larvae needed. For example, *A. hybridus* leaves had 29% carbohydrate and 34.8% protein (Adeyeye & Omolayo, 2011). However, *Z. mays* leaves had a higher content of carbohydrates (69.25%) but a lower protein content (8.70%) (Ayaşan et al., 2020). *I. aquatic* leaves had 2.87% carbohydrate and 7.54% protein (Shariff et al., 2019). *I. reptans* leaves contained 31.8% carbohydrate and 32.2% protein (Kalita et al., 2007). Insects need protein or essential amino acids and carbohydrates and that are properly balanced about proteins and carbohydrates (Pinto et al., 2019).

The lower larval mortality occurred on diets enriched with *Z. mays*, *I. reptans*, *I. aquatica*, *A. hybridus*, and *M. rubra* leaves and the higher larval mortality occurred on diets enriched with *B.*

mutica and *S. sphacelata* leaves. However, the diet enriched with *M. rubra* could decrease the eggs laid by the female *S. frugiperda* and could increase the abnormal pupae. The diets enriched with *S. sphacelata* and *B. mutica* leaves could increase a percentage of abnormal pupae and decrease a percentage of adult emergence. Abnormal pupae underwent malformation and could not emerge to be an adult. The lower adult emergence and higher abnormal pupae also occurred on diets enriched with *B. mutica* and *S. sphacelata* leaves. Therefore, the artificial diets enriched with *B. mutica*, *S. sphacelata*, and *M. rubra* leaves were not suitable to increase the growth and development of *S. frugiperda*. *B. mutica*, *S. sphacelata*, and *M. rubra* leaves had higher content of protein and carbohydrate, i.e., *M. rubra* (Iqbal et al., 2012)*, B. mutica* (Alam et al., 2015), and *S. sphacelata* (Kamaruddin et al., 2021) leaves had 24.63%, 3.82%, and 11.80% protein, respectively, and 28.37%, 23.72%, and 77.92% carbohydrate, respectively. However, data showed that the value of the relative growth rate (RGR) of diets enriched with *B. mutica*, *S. sphacelate*, and *M. rubra* leaves was low. It indicated that the growth and development of *S. frugiperda* did not only influence by primary compounds (nutritional components), protein and carbohydrates, but also influenced by secondary metabolites (Rahayu et al., 2023), such as terpenoids and alkaloids which are antifeedant (Rattan, 2010). *M. alba* leaf extract could inhibit the growth of *Lymantria dispar* L. because it has antifeeding activities against the insect (Gvozdenac et al., 2012). Because *B. mutica* leaf extract has insecticidal activity so that it could decrease fecundity and survival rate of *Leptocorisa oratorius* (F.) (Morrill et al., 1990). *Setaria viridis* (L.) leaf extract had larvicidal activities against *Anopheles stephensi* Liston and *Culex quinquefasciatus* Say (Ashok & Babu, 2021). The current study showed that the artificial diets enriched with *B. mutica*, *S. sphacelata*, and *M. rubra* leaves could increase larval mortality and a percentage of abnormal pupae, and decrease a percentage of *S. frugiperda* adult emergence. These data indicated that *B. mutica*, *S. sphacelate,* and *M. rubra* leaves had insecticidal activities; therefore, for this reason, they needed to be studied further. In addition, water content, shape, and hardness (physical characteristics) also play an important role in affecting assimilation and the efficiency of diet intake (Pinto et al., 2019).

In the current research, the diets enriched with *B. mutica*, *S. sphacelata*, and *M. rubra* leaves were harder than those enriched with other diets. The diets enriched with *Z. mays*, *I. reptans*, *I. aquatica*, and *A. hybridus* leaves were more attractive to the *S. frugiperda* larvae. Next study needed to evaluate the physical characteristics and the nutritional content of the diets and to maintain the diets for a longer time.

The developmental time of *S. frugiperda* consuming artificial diets enriched with *A. hybridus*, *I. reptans*, and *I. aquatic* leaves was similar to the diet enriched with *Z. mays* leaves and shorter compared to developmental time from the diets enriched with *M. rubra*, *S. sphacelata*, and *B. mutica* leaves. Diet nutritional quantitatively and qualitatively can cause differences in the growth and developmental time of *S. frugiperda*, and the nutritional diets can produce more eggs laid and heavier larvae and pupae (Pinto et al., 2019). The adult females from larvae consuming diets enriched with *A. hybridus*, *Z. mays*, *I. reptans*, *I. aquatica*, and *S. sphacelata* leaves could lay more eggs (fecundity) compared to those of other diets and their eggs had higher fertility. However, diet enriched with *S. sphacelata* leaves caused higher larval mortality. Thus, the more suitable diets to increase the larval growth and survival and adult emergence and fecundity were those enriched with *A. hybridus*, *Z. mays*, *I. reptans*, and *I. aquatic* leaves. The variability in *S. frugiperda* adult fecundity was regulated by food or diet consumed by their larvae (Wheeler, 1996). *Z. mays* (control) was a crop with a higher economic value than wild host plants (*A. hybridus*, *I. reptans* and *I. aquatic*). Because *Z. mays* was not a weed or wild host plant, so the better choice for the artificial diets based on the cost/benefit ratio (*Z. mays* and weeds) was the diets enriched *A. hybridus*, *I. reptans*, and *I. aquatic. A. hybridus* (land weed), *I. reptans* (aquatic weed), and *I. aquatic* (aquatic weed) are wildly grown without the necessity of being cultivated. Our research highlighted that the use of weed or wild host plant leaves for producing artificial diets is feasible for mass-rearing *S. frugiperda.* The use of weed leaves could reduce the cost of the artificial diet.

CONCLUSION

The suitable diets to increase the larval growth and survival, and adult emergence and fecundity of *S. frugiperda* were the diets enriched with *Z. mays*, *A. hybridus*, *I. reptans*, and *I. aquatic* leaves. Thus, the diets enriched with *Z. mays*, *A. hybridus*, *I. reptans*, and *I. aquatic* leaves were suitable for *S. frugiperda* growth and development. However, the better choice for the artificial diets based on wild host plants or weed was the diets enriched *A. hybridus*, *I. reptans*, and *I. aquatic.* The use of weed or wild host plant leaves for producing artificial diets is feasible for mass-rearing *S. frugiperda.* It needed to be further investigated that the use of weed leaves could reduce the cost of the artificial diet.

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