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Balanites aegyptiaca and *Calotropis procera* aqueous extracts exhibit ovicidal and larvicidal activity against *Spodoptera frugiperda*

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Résumé

La lutte botanique apparaît comme une alternative prometteuse pour les petits producteurs. La présente étude évalue les effets ovicides et larvicides d'extraits aqueux du dattier du désert (*Balanites aegyptiaca*) et du pommier de Sodome (*Calotropis procera*) sur la chenille légionnaire d'automne (*Spodoptera frugiperda*). Pour cela, cinq concentrations de chaque extrait ont été testées sur les œufs d'un jour et les larves de deuxième stade. Le taux d'inhibition de l'éclosion des œufs ainsi que le taux de mortalité des larves ont été calculés. Les concentrations inhibitrices de 50% de l'éclosion des œufs (CI_{50}) et les concentrations létales 50% (CL_{50}) ont été déterminées. Les résultats révèlent que les concentrations de 148 g/L, 185 g/L et 222 g/L de *B. aegyptiaca* et 126 g/L et 152 g/L de *C. procera* ont maintenu une inhibition de l'éclosion des œufs au-dessus de 50 % à 168 h après application, contre 2% pour le témoin. À 96 h, la CI_{50} de *C. procera* (12,70 g/L) était inférieure à celle de *B. aegyptiaca* (126,35 g/L). Concernant l'effet larvicide, l'extrait de *B. aegyptiaca* a atteint une mortalité maximale de 83,93 % à 222 g/L, tandis que les concentrations de *C. procera* ont induit plus de 50 % de mortalité. À 24 h, la CL_{50} de *B. aegyptiaca* était de 120,75 g/L contre 137,41 g/L pour *C. procera*. Les extraits aqueux de *B. aegyptiaca* et *C. procera* sont de potentiels alternatifs durables pour la gestion de *Spodoptera frugiperda*.

Mots-clés : Lutte botanique, *Balanites aegyptiaca*, *Calotropis procera*, espèces invasives, *Zea mays*, Bénin

Abstract

The use of botanical control is increasingly being considered as a sustainable alternative to chemical control, especially for smallholder farmers with limited financial resources. This study aimed to evaluate the ovicidal and larvicidal effects of the aqueous extracts of *Balanites aegyptiaca* and *Calotropis procera* on fall armyworm (*Spodoptera frugiperda*). To this end, five concentrations of each extract were tested on one-day-old eggs and on second-instar larvae. The egg hatching inhibition rate and larval mortality rate were calculated. The 50% inhibitory concentrations for egg hatching (IC_{50}) and the 50% lethal concentrations (LC_{50}) were determined. The results revealed that concentrations of 148 g/L, 185 g/L, and 222 g/L of *B. aegyptiaca* and those of 126 g/L and 152 g/L of *C. procera* maintained egg hatching inhibition above 50% at 168 h after application, which was not the case on control treatment, where 98% of eggs hatched within the same time slot. At 96 h, the IC_{50} of *C. procera* (12.70 g/L) was significantly lower than that of *B. aegyptiaca* (126.35 g/L). Regarding the larvicidal effect, the extract of *B. aegyptiaca* induced a maximum mortality of 83.93% at 222 g/L, while all concentrations of *C. procera* induced more than 50% mortality. At 24 h, the LC_{50} of *B. aegyptiaca* was 120.75 g/L compared to 137.41 g/L for *C. procera*. The aqueous extracts of *B. aegyptiaca* and *C. procera* are therefore potential sustainable alternatives for the management of *S. frugiperda*.

Keywords: Botanical control, *Balanites aegyptiaca, Calotropis procera.* invasive species, *Zea mays*, Benin

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1. Introduction

Maize (*Zea mays* L.) is one of the main cereal crops cultivated worldwide. It plays a fundamental role in food security. In Africa, maize is the staple food for a large part of the population (Aleri et al., 2026; Santpoort, 2020), providing nearly one-third of annual caloric intake (Macauley & Ramadjita, 2015). This cereal is cultivated on more than 40 million hectares of land in Africa, with a production of over 90 million metric tons (FAOSTAT, 2024). In Africa, the production of this cereal is threatened by numerous abiotic and biotic hazards, including insect pests (Salika et al., 2021; Kasoma et al., 2020; Hardwick et al., 2019). These constraints are among the main factors of low yield records of the crop in Africa, which remain below 2 t/ha, compared to the global average of 5 t/ha (Erenstein et al., 2022). In addition to lepidopteran stem borers causing damage to maize crops (Sokame et al., 2023), the fall armyworm, *Spodoptera frugiperda* (J. E. Smith, 1797; Lepidoptera: Noctuidae), has emerged as a top priority pest over the last decade.

The fall armyworm was first detected in Africa in 2016 (Goergen et al., 2016). It is a polyphagous pest that primarily attacks maize (*Zea mays*) (Montezano et al., 2018). In sub-Saharan Africa, almost all cultivated maize varieties are susceptible to attack by this pest (Prasanna et al., 2018), making it a major threat to food security on the continent. The fall armyworm could cause production losses ranging from 21 to 53% per year, corresponding to economic losses of approximately USD 2.5–6.2 billion (Day et al., 2017). These losses are among the key drivers of food insecurity. They also negatively affect smallholder farmers' livelihoods and income (Bannoret al., 2022). To minimize losses, these farmers mainly rely on the use of synthetic chemical pesticides (Pavela, 2016). However, chemicals are generally highly toxic to the environment and humans (Carvalho, 2017). In addition, they are becoming increasingly ineffective as the fall armyworm is developing resistance to most available pesticides (Schlum et al., 2021; Baudron et al., 2019). The adoption of sustainable alternatives such as biopesticides has become imperative for effective management of the fall armyworm.

The limitations of chemical control, climate change effects, and the growing demand for chemical residue-free food are gradually placing biopesticides at the center of agricultural production, particularly in Africa. Biopesticides are environmentally friendly and known to be safer for human health, unlike synthetic chemical pesticides (Nxumalo et al., 2021; Paredes-Sánchez et al., 2021). They are therefore well-suited for sustainable pest control strategies and can be used against *S. frugiperda*. Among biopesticides, botanical pesticides occupy an important place. The use of botanical insecticides is being increasingly advocated for controlling crop pests (Nxumalo et al., 2021). They are locally available (Reddy & Chowdary, 2021), and their use is economically profitable (Pavela, 2016). In fact, several botanical insecticides have been tested against *S. frugiperda* both in its area of origin and in the new areas it has invaded (Adikpéto et al., 2025; Phambala et al., 2020; Sisay et al., 2019), particularly in Benin. However, there are still knowledge gaps worth exploring for their effective context-specific use.

A survey we conducted in 2024 in northern, central, and southern Benin identified some 20 insecticidal plant species used by farmers to control crop pests, including the fall armyworm. The desert date (*Balanites aegyptiaca* (L.) Delile) and the apple of Sodom (*Calotropis procera* (Aiton) W.T.Aiton) are among the common species used by farmers. These two insecticidal plant species are used by many of the surveyed farmers and are at instances considered effective against insect pests. In addition, several studies reported the insecticidal properties of these two species against various insect pests. Extracts of *B. aegyptiaca* have been reported to be effective against mosquitoes and some animal pathogens (Shalaby et al., 2012; Chapagain et al., 2008). Similarly, Bader et al. (2021) found that *C. procera* extract had an insecticidal effect on the stored-product pest moth, *Cadra cautella* (Walker, 1863), as well as on mosquitoes (Marc, 2021). However, the actual effectiveness and optimal doses of the two insecticidal plant species against fall armyworm have not yet been scientifically established and disseminated. This could explain disagreements in farmers' views regarding the effectiveness of the plants' extracts. Therefore, a crucial research question was formulated regarding the optimal insecticidal doses of the aqueous extracts of *B. aegyptiaca* and *C. procera*. The present study aimed to evaluate the ovicidal and larvicidal effects of the aqueous extracts of *B. aegyptiaca* and *C. procera* on the fall armyworm under laboratory conditions. Specifically, this study (i) evaluated the effect of different concentrations of aqueous extracts of *B. aegyptiaca* and *C. procera* on egg hatching and the mortality of second-instar larvae of the fall armyworm and (ii) determined the 50% inhibitory concentrations for egg hatching (IC_{50}) and the 50% lethal concentrations (LC_{50}). We assumed that the aqueous extracts of *B. aegyptiaca* and *C. procera* cause concentration-dependent larval mortality and ovicidal effects. This study provides a scientific basis for a rational use of these extracts in fall armyworm management.

2. Material and methods

2.1. Collection of plant material and preparation of extracts

2.1.1. Collection of plant material

More than 500 food crop farmers were surveyed in the municipalities of Kandi, Bembèrèkè, Djidja, Adjohoun, and Kétou in Benin. These municipalities are among the largest producers of food crops in Benin, specifically maize. This led to the identification of twenty key insecticidal plant species used by farmers to control crop pests. Among these species are *B. aegyptiaca* and *C. procera*, which are used by many farmers in the surveyed locations. Thus, the leaves of *B. aegyptiaca* and *C. procera* were collected in Kandi (11°07′43″ north and 2°56′13″ east), in northern Benin. They were stored in coolers and carried to the laboratory.

2.1.2. Preparation of extracts

The aqueous extracts were prepared by macerating crushed fresh leaves in distilled water. A pre-test was conducted to determine the median concentrations per each insecticidal plant species. Final concentrations were calibrated based on the median concentrations. Thus, for each aqueous extract, a series of concentrations was tested on 20 second-instar *S. frugiperda* larvae by topical application. The initial concentration resulting in 50% larval mortality (noted as C_iL50) for each of the two species was determined using probit analysis (Finney, 1971). This resulted in concentrations of 148 g/L and 101 g/L for the aqueous extracts of *B. aegyptiaca* and *C. procera*, respectively. The five experimental concentrations tested were defined around these concentrations, i.e.,

$0.5*C_iL_{50}$; $0.75*C_iL_{50}$, $1.0*C_iL_{50}$, $1.25*C_iL_{50}$ and $1.5*C_iL_{50}$. Therefore, concentrations of 74 g/L, 111 g/L, 148 g/L, 185 g/L, and 222 g/L (weight/volume) were tested for *B. aegyptiaca*. Conversely, the concentrations tested for *C. procera* were 51 g/L, 76 g/L, 101 g/L, 126 g/L, and 152 g/L (fresh weight/volume). For each concentration, the corresponding leaf weights were collected and crushed using a laboratory mortar. The crushed samples were each placed in an Erlenmeyer flask and supplemented with 100 mL of distilled water and 0.2 g of Omo Klin adjuvant (Adikpeto et al., 2025). The solution was vortexed and left to macerate for 48 h before use. After this period, the mixtures were filtered, and the resulting filtrates were used for the different bioassays.

2.2. Ovicidal bioassay

The ovicidal effect of aqueous extracts, from both insecticidal plant species, *B. aegyptiaca* and *C. procera*, was tested on 24-hour-old eggs of the fall armyworm (Sombra et al., 2020). The eggs, laid on tissue paper, were carefully divided into batches of 60 eggs each and then transferred to Petri dishes (Vijitkul et al., 2025). For each concentration, a total of 300 eggs were used, organized into 5 replicates of 60 eggs each. A volume of two hundred microliters (200 µL) of each solution was sprayed onto each replicate using a hand sprayer (Sombra et al., 2020). The same procedure was followed for the five concentrations of the different botanical extracts, as well as for the control (distilled water + 0.2 g of Omo Klin). The number of hatched eggs was recorded daily for 7 days (Sombra et al., 2020). The bioassay was conducted at the Biorisk Management Facility (BIMAF) laboratory of the International Institute of Tropical Agriculture (IITA) in Benin, under controlled conditions of temperature (26 ± 1 °C), relative humidity (65-70%), and photoperiod (12 hours of light: 12 hours of darkness).

The hatching inhibition rate was calculated using the formula as follows (Moungthipmalai et al., 2023):

$$\textbf{Inhibition rate}\ (\%) = 100 - \left[\left(\frac{Number\ of\ eggs\ hatched}{Total\ number\ of\ eggs}\right) x\ 100\right]$$

2.3. Larvicidal bioassay

The toxicity test was performed on second instar (L2) larvae of *S.podoptera frugiperda* by topical application, according to the method described by Sombra et al. (2020), with slight modifications. A volume of 2 µL of each solution was applied to the thorax of each larva using a micropipette. Distilled water + 0.2 g of Omo Klin adjuvant was used on control treatments. For each concentration, 60 larvae were used, i.e., 5 replicates of 12 larvae each (Bordin et al., 2023). To avoid cannibalism, each larva was placed individually in a Petri dish after treatment, and fed with untreated sprouting maize leaves. The experiment was conducted using a completely randomized block design. Larval mortality was recorded 24, 48, and 72 h after application, according to the method described by Ammar et al. (2025). A larva was considered dead if it did not react or was unable to move when stimulated with a fine brush (Lourenço et al., 2018). The test was conducted under the same laboratory conditions as the ovicidal bioassay.

The percentage of dead larvae was calculated using the following formula:

$$\textbf{Larval mortality}\ (\%) = \frac{\text{Number of dead larvae}}{\text{Total number of larvae treated}}\ x\ 100$$

When mortality in the control group was greater than or equal to 5%, Abbott's formula (1925) was used to obtain the corrected mortality:

$$\textbf{Corrected mortality}\ (\%) = \frac{Mo - Me}{100 - Me}\ x\ 100$$ where *Mc* is the corrected mortality (%), *Mo* is the observed mortality in each treatment (%), and *Me* is the mean mortality observed in the control (%).

2.4. Statistical analysis

Survival analyses were performed using GraphPad Prism 10 software. The Kaplan-Meier method was applied to estimate larval survival probabilities under the different treatments. Survival curves were compared using the log-rank (Mantel-Cox) test, and the Gehan-Breslow-Wilcoxon test was performed to evaluate the early effect of the treatments on larval survival. In addition, the effects of treatments on egg hatching and larval mortality were analyzed using generalized linear models (GLM) (Nelder & Wedderburn, 1972). When effects were significant, multiple comparisons of adjusted means were performed using the emmeans package. Probit analysis of the concentration–mortality and concentration–egg inhibition data was done to determine the 50% lethal concentrations (LC_{50}) and the 50% inhibitory concentrations (IC_{50}) (Finney, 1971). The level of statistical significance was set at $p < 0.05$. These analyses were performed using R software version 4.4.0 (R Core Team, 2024).

3. Results

3.1. Ovicidal effect and median inhibitory concentration of aqueous extracts of *Balanites aegyptiaca* and *Calotropis procera* on *S. frugiperda*

3.1.1. Ovicidal effect of aqueous extracts of *Balanites aegyptiaca* and *Calotropis procera* on *Spodoptera frugiperda*

The aqueous extracts of *B. aegyptiaca* and *C. procera* exhibited significant ovicidal activity against *S. frugiperda*. Egg hatchability decreased progressively with increasing extract concentration, with *C. procera* exhibiting a comparatively greater inhibitory effect (Figure 1). These findings indicate the potential of both insecticidal plant species as effective botanical agents for managing early developmental stages of the pest.

Indeed, the GLM analysis showed a significant effect of extract concentration on egg hatching inhibition ($p < 0.001$). For *B. aegyptiaca*, all concentrations achieved 100% egg inhibition at 24 h, followed by a decline at 96 h post-treatment (26–65%), with the highest concentrations causing more than 50% inhibition rate at 168 h.

Similarly, *C. procera* exhibited strong ovicidal activity at 24 h. At 96 h, lower concentrations showed reduced efficacy, whereas higher concentrations induced more than 70% inhibition rate, with a maximum of 79.34% egg inhibition reached. At 168 h, the egg inhibition rate decreased at lower concentrations (<40%) but remained between 50% and 69% at the highest concentrations (Table 1).

Overall, both extracts demonstrated significant and concentration-dependent ovicidal effects compared to the control.

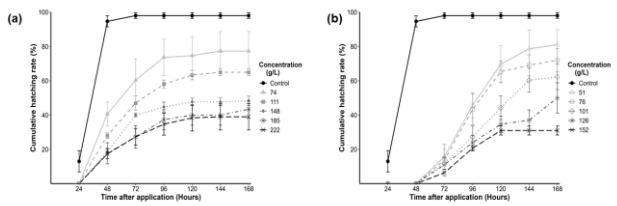

Figure 1. Cumulative egg hatching rate of fall armyworm after application of different concentrations of Balanites aegyptiaca's (a) and Calotropis procera's (b) aqueous extracts. (Taux d'éclosion cumulé des œufs de la chenille légionnaire d'automne après application de différentes concentrations d'extraits aqueux de Balanites aegyptiaca (a) et de Calotropis procera (b)).

Table 1. Inhibition rate of fall armyworm egg hatching after application of different concentrations of Balanites aegyptiaca's and Calotropis procera's aqueous extracts. (Taux d'inhibition de l'éclosion des œufs de la chenille légionnaire après application de différentes concentrations d'extraits aqueux de Balanites aegyptiaca et Calotropis procera)

Species	Concentrations (g/L)	Means ± Standard error		
		24h	96h	168h
Balanites aegyptiaca	**Control**	87.00 ± 6.20a	2.00 ± 1.62a	2.00 ± 1.62a
	74	100 ± 0.00a	26.33 ± 10.59ab	22.67 ± 11.41ab
	111	100 ± 0.00a	42.00 ± 2.38bc	35.00 ± 2.11bc
	148	100 ± 0.00a	55.33 ± 2.95c	51.67 ± 2.69bc
	185	100 ± 0.00a	62.67 ± 5.74c	56.67 ± 5.06c
	222	100 ± 0.00a	65.33 ± 6.40c	61.00 ± 7.72c
Calotropis procera	**Control**	87.00 ± 6.20a	2.00 ± 1.62a	2.00 ± 1.62a
	51	100 ± 0.00a	54.32 ± 7.40b	19.00 ± 8.87ab
	76	100 ± 0.00a	56.68 ± 9.08bc	28.00 ± 6.78abc
	101	100 ± 0.00a	72.68 ± 6.28bc	37.68 ± 7.45bcd
	126	100 ± 0.00a	76.02 ± 4.05bc	50.00 ± 8.85cd
	152	100 ± 0.00a	79.34 ± 1.54c	69.02 ± 2.61d

For each plant species, means with the same letters in the column are not significantly different, α=5%. (Pour chaque espèce végétale, les moyennes suivies de la même lettre dans la colonne ne sont pas significativement différentes (α = 5 %))

3.1.2. Median Inhibitory Concentration (IC_{50}) of the aqueous extracts of Balanites aegyptiaca and Calotropis procera

The variation in median inhibitory concentration (IC_{50}) of aqueous extracts of *B. aegyptiaca* (Fig. 2a) and *C. procera* (Fig. 2b) on the fall armyworm revealed that the concentration required to inhibit the hatching of 50% of eggs increased gradually over time for both plant extracts. Likewise, the concentration of *B. aegyptiaca* extract required to inhibit the hatching of 50% of *S. frugiperda* eggs in 96 h was 126.35 g/L, while 242.17 g/L was required to inhibit 50% of the eggs in 168 h.

In contrast to *B. aegyptiaca*, 12.70 g/L of the aqueous extract of *C. procera* is needed to inhibit 50% of the eggs in 96 h, while to maintain this inhibition over 168 h, nearly 25 times this concentration (297.51 g/L) is required.

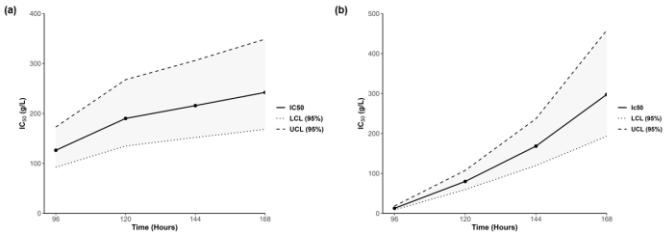

Figure 2. Temporal variation of IC_{50} values for fall armyworm egg hatching inhibition by Balanites aegyptiaca (a) and Calotropis procera (b). (Variation temporelle des valeurs CI_{50} pour l'inhibition de l'éclosion des œufs de la chenille légionnaire d'automne par Balanites aegyptiaca (a) et Calotropis procera (b)).

3.2. Larvicidal effect and variation in 50% lethal concentrations of the aqueous extracts of Balanites aegyptiaca and Calotropis procera on Spodoptera frugiperda

3.2.1. Larvicidal effect and variation in 50% lethal concentrations of the aqueous extracts of Balanites aegyptiaca and Calotropis procera on Spodoptera frugiperda

The Logrank (Mantel-Cox) test revealed that the survival of fall armyworm larvae was significantly affected by the application of both aqueous extracts of *C. procera* (χ^2= 62.87; $p < 0.001$) and *B. aegyptiaca* (χ^2= 95.46; $p < 0.001$). The probability of survival decreased gradually over time. The decline was significantly prominent in the plant extracts' treatments compared to control (Fig. 3). Furthermore, the results of the Gehan-Breslow-Wilcoxon test revealed that the effect on larval survival is evident within the first few hours after application of the treatments for both *B. aegyptiaca* extract (χ^2= 99.78; $p < 0.001$) and *C. procera* extract (χ^2= 65.28; $p < 0.001$).

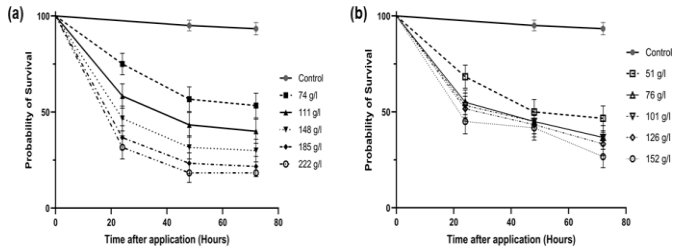

Figure 3. Larval survival of fall armyworm after treatment with different concentrations of Balanites aegyptiaca *(a) and* Calotropis procera *(b). (Survie des larves de la chenille légionnaire d'automne après traitement avec différentes concentrations de Balanites aegyptiaca (a) et Calotropis procera (b)).*

The generalized linear model (GLM) results showed that the treatments had a highly significant effect on larval mortality ($p < 0.001$). Indeed, at 24 h post-treatment, among the five *B. aegyptiaca* concentrations, the lowest larval mortality was observed at 74 g/L (25.00 ± 2.63), while the highest was at 222 g/L (68.33 ± 3.12%). Nevertheless, the mortality of larvae induced by the concentration of 222 g/L was not significantly higher than that caused by 148 g/L and 185 g/L. The larval mortality resulting from the five concentrations of *B. aegyptiaca* was significantly

higher than that of the control from 48 h onward after treatment. Although the larval mortality increased at each concentration 72 h after treatment, the highest was at 222 g/L (83.93 ± 1.79%).

The larval mortality induced by the five concentrations of *C. procera* was relatively low 24 h post-treatment compared to the different concentrations of *B. aegyptiaca*. The lowest larval mortality was observed at the 51 g/L concentration (31.67 ± 3.12%). At 72 h post-treatment, no significant difference in larval mortality was observed among the tested concentrations even though the concentration of 152 g/L induced 71.43 ± 1.78% mortality and the concentration of 51 g/L resulted in 50.00 ± 2.19% mortality. These mortality rates are all higher than those observed in the control (6.67 ± 3.12%).

3.2.2. Variation in 50% lethal concentrations (LC_{50}) of the aqueous extracts of Balanites aegyptiaca and Calotropis procera

The median lethal concentrations (LC_{50}) decreased progressively over time for both aqueous extracts of *B. aegyptiaca* (Fig. 4a) and *C. procera* (Fig. 4b). The aqueous extract of *C. procera* was the most toxic at 24 h with an LC_{50} of 120.75 g/L compared to 137.41 g/L for the aqueous extract of *B. aegyptiaca*. However, at 48 and 72 h, the LC_{50} values for the aqueous extract of *B. aegyptiaca* were the lowest (22.80 g/L and 14.89 g/L) compared to those of *C. procera*, which were 48.46 g/L and 15.77 g/L, respectively.

Table 2. Larval mortality of fall armyworm after treatment with different concentrations of Balanites aegyptiaca and Calotropis procera. (Mortalité larvaire de la chenille légionnaire d'automne après traitement avec différentes concentrations de Balanites aegyptiaca et Calotropis procera)

Species	Concentrations (g/L)	Means ± Standard error		
		24h	48h	72h
Balanites aegyptiaca	Control	0.00 ± 0.00a	5.00 ± 2.04a	6.67 ± 3.12a
	74	25.00 ± 2.63a	40.35 ± 1.75b	42.86 ± 2.19b
	111	41.67 ± 2.64ab	54.39 ± 3.28bc	57.15 ± 1.79bc
	148	53.33 ± 2.04bc	66.66 ± 1.75bcd	67.86 ± 2.18bcd
	185	63.33 ± 3.33bc	75.44 ± 3.28cd	76.78 ± 2.19cd
	222	68.33 ± 3.12c	80.70 ± 3.28d	83.93 ± 1.79d
Calotropis procera	Control	0.00 ± 0.00a	5.00 ± 2.04a	6.67 ± 3.12a
	51	31.67 ± 3.12a	50.00 ± 2.63b	50.00 ± 2.19b
	76	45.00 ± 2.04b	55.00 ± 2.04b	60.72 ± 3.57b
	101	46.67 ± 2.04b	55.00 ± 2.04b	60.72 ± 2.19b
	126	48.33 ± 1.67b	56.66 ± 1.67b	64.29 ± 2.82b
	152	55.00 ± 2.04b	58.33 ± 2.64b	71.43 ± 1.78b

For each plant species, means with the same letters in the column are not significantly different, α=5%. (Pour chaque espèce végétale, les moyennes suivies de la même lettre dans la colonne ne sont pas significativement différentes (α = 5 %))

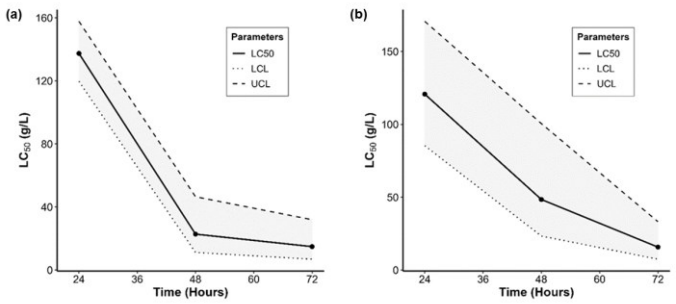

Figure 4. Temporal variation of LC_{50} values for fall armyworm larval mortality induced by Balanites aegyptiaca (a) and Calotropis procera (b). (Variation temporelle des valeurs de CL_{50} de la mortalité des larves de la chenille légionnaire d'automne induite par Balanites aegyptiaca (a) et Calotropis procera (b)).

4. Discussion

The use of plant extracts for crop pest management is a sustainable alternative, particularly in the context of climate change.

The results revealed a high egg hatching rate (95%) in the control as early as three days after oviposition. This can be explained by favorable experimental conditions, including optimal temperature and humidity, as well as the high viability of the eggs. Furthermore, the egg hatching rate is comparable to those reported in the wild for *S. frugiperda* and other closely related pests, according to previous studies (Montezano et al., 2019; Specht & Roque-Specht, 2016; Busato et al., 2008). In addition, the incubation period of *S. frugiperda* eggs in the control group is consistent with that reported by other authors under similar conditions and without treatment application (Kumar et al., 2024; Montezano et al., 2019). This indicates that distilled water and Omo Klin adjuvant did not affect the hatching or the incubation period of fall armyworm eggs. On the aqueous extract treatments, egg hatching was affected and stretched over time as a consequence of *B. aegyptiaca*'s or *C. procera*'s insecticidal properties. The egg hatching was delayed by more than four days, regardless of the concentrations of these treatments. The bioactive compounds in these two extracts, therefore, appear to interfere with the physiological mechanisms involved in larval emergence. Banerjee et al. (2014) reported that applying aqueous extract of neem (*Azadirachta indica*) to the early stages of development of the eggs of the fish ectoparasite *Argulus bengalensis* (Ramakrishna, 1951) delayed the embryonic development, resulting in delayed hatching. Under field conditions, this delay can desynchronize larval emergence against food resource availability. In addition, it can promote greater exposure of eggs to egg and egg-larval parasitoids such as *Telenomus remus* and *Chelonus* sp. (Kenis et al., 2019; Tendeng et al., 2019; Hay-Roe et al., 2015). This may potentially result in an increase of the natural reduction of *S. frugiperda*'s populations in the field.

The results of this study also showed that at the end of the observation period, 168 h after the application of the treatments (approximately eight days after egg laying), a proportion of fall armyworm eggs remained unhatched. This observation suggests that the aqueous extracts of *B. aegyptiaca* and *C. procera* exhibit ovicidal activity against *S. frugiperda* eggs. Previous studies have already reported the ovicidal effect of *B. aegyptiaca* methanolic extract on other parasites such as the worm *Toxocara vitulorum* (Goeze, 1782) (Shalaby et al., 2012). The ovicidal

property is thought to be caused by Balanitin-7, a steroidal saponin (Gnoula et al., 2007). Studies by Bader et al. (2021) have also shown the ovicidal effect of *C. procera* on *Cadra cautella*, mainly owing to 15β-hydroxy-calactin. Isolating Balanitin-7 and 15β-hydroxy-calactin and testing them on fall armyworm eggs could provide more insight into their contribution to the current observed ovicidal effect.

Regarding the egg hatching inhibition induced by the aqueous extract of *B. aegyptiaca*, the results specifically revealed that concentrations of 148 g/L, 185 g/L, and 222 g/L maintained the highest inhibition of egg hatching at the end of the experiment, with no significant difference between these concentrations. This suggests that a concentration of 148 g/L would be sufficient to achieve the maximum ovicidal effect of the aqueous extract of *B. aegyptiaca* against *S. frugiperda*. On the other hand, the extract concentrations of 126 g/L and 152 g/L of *C. procera* showed more than 50% inhibition. The findings indicate that the ovicidal effect of *C. procera*'s extract is concentration-dependent compared to that of *B. aegyptiaca*. This agrees with our hypothesis that *C. procera* extract has a concentration-dependent ovicidal effect on *S. frugiperda*. Likewise, a couple of studies have reported the concentration-dependent ovicidal effect of *C. procera* on other species (Okeke et al., 2022; Bader et al., 2021).

Regarding the 50% inhibitory concentrations (IC_{50}), the results revealed that for the aqueous extract of *B. aegyptiaca*, 126.35 g/L was required 96 h after application, while a concentration of 242.17 g/L was necessary to maintain this inhibition 168 h after treatment. This suggests a gradual decline in the ovicidal efficacy of *B. aegyptiaca* over time. In contrast, the aqueous extract of *C. procera* gave rise to relatively low IC_{50} at 96 h (12.70 g/L), suggesting high early ovicidal toxicity. Nevertheless, a concentration nearly 25 times higher than the previous one was required to achieve 50% inhibition of hatching 168 h after treatment. This indicates a drastic loss of ovicidal persistence of *C. procera* over time. The results demonstrate that, although both extracts show significant ovicidal activity against *S. frugiperda*, *B. aegyptiaca* appears to show more stable efficacy over time, while *C. procera* acts mainly rapidly, requiring increasing concentrations to prolong its effect.

In terms of the effect of the treatments on fall armyworm larvae, the results revealed that only 6% larval mortality was observed in the control group (distilled water and Omo Klin adjuvant). This mortality rate is slightly above the natural mortality rate of approximately 2% reported by Montezano et al. (2019), but comparable to that reported by Giolo et al. (2002). Concerning the aqueous extracts of *B. aegyptiaca* and *C. procera*, it was discovered that the effect on the larval survival was evident within the first few hours after application of the treatments, suggesting that their action was rapid. Furthermore, at the end of the observation period (72 h after treatment), the mortality rates induced by the different concentrations of the aqueous extract of *C. procera* were equivalent. The aqueous extract of *C. procera* therefore, had no concentration-dependent larvicidal effect on the fall armyworm in this study, in contrast to our hypothesis. The larvicidal effect of *C. procera* on mosquitoes in particular has been reported in several studies (Marc, 2021; Govindarajan et al., 2012; Elimam et al., 2009; Singh et al., 2005), generally showing a concentration-dependent trend. This obviously evokes specific variations across insect species and extract's compounds involved. In fact, several studies have highlighted disparities in the chemical composition of insecticidal plants depending on the harvest period, geographical location, and other environmental factors (Hazrati et al., 2022; Paulus et al., 2019; Rimkiene et al., 2017). The larvicidal activity of *C. procera* is likely attributable to the presence of cardiac glycosides (cardenolides), which are known to act on the cardiovascular, neurological, and gastrointestinal systems (Wang et al., 2008). Unlike *C. procera*, the aqueous extract of *B. aegyptiaca* exhibited a concentration-dependent larvicidal effect on the fall armyworm larvae, as we assumed. This difference in the larvicidal effect between *B. aegyptiaca* and *C. procera* may be due to the phytochemical composition of these two plant species. *B. aegyptiaca* likely contains a limited number of major active compounds whose efficacy increases with concentration, whereas *C. procera* probably contains several active ingredients that act synergistically, resulting in maximum efficacy at low doses. Future studies on the phytochemical profile of the aqueous extracts of these two species could provide further clarification. Indeed, previous studies have reported the effect of *B. aegyptiaca* extracts on nematodes (Shalaby et al., 2019; Ibrahim, 1992) and mosquito larvae (Chapagain et al., 2008; Wiesman & Chapagain, 2006; Zarroug et al., 1990).

The results also revealed that the aqueous extract of *C. procera* had the lowest LC_{50} at 24 h, while that of *B. aegyptiaca* showed the lowest LC_{50} values at 48 and 72 h. This observation suggests that the bioactive compounds present in *C. procera* act more rapidly on *S. frugiperda* larvae, while the larvicidal effect of *B. aegyptiaca* may be more gradual but more sustained over time.

5. Conclusion

The findings indicate that the ovicidal effect of *C. procera*'s extract is concentration-dependent compared to that of *B. aegyptiaca* on fall armyworm eggs. In contrast, the aqueous extract of *B. aegyptiaca* exhibited a concentration-dependent larvicidal effect on the fall armyworm larvae, as opposed to *C. procera*. The aqueous extract of *C. procera* exhibited a rapid ovicidal and larvicidal effect on the fall armyworm, while *B. aegyptiaca* has a slower but stable insecticidal activity over time. These results support the potential of the aqueous extracts of *B. aegyptiaca* and *C. procera* as botanical alternatives in the sustainable management of fall armyworm. However, further field validation studies are needed to confirm their efficacy and evaluate their synergism with other integrated pest management options.

Credit authorship contribution statement

Moret Burnier Sènalèkokpon Adikpéto: Conceptualization, Investigation, Methodology, Writing – original draft. Ghislain T. Tepa-Yotto: Conceptualization, Investigation, Writing – review & editing, Funding acquisition. Kossiba Jeannette Winsou: Investigation, Writing – review & editing. Mintognissè Donald Estelle Adikpéto: Investigation, Writing – review & editing. Elie A. Dannon: Supervision, Writing – review & editing. Appolinaire Adandonon: Supervision, Writing – review & editing. Yêyinou Laura Estelle Loko: Supervision, Writing – review & editing.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The funders had no role in the design of the study; in the assemblage and interpretation of data; in the writing of the review paper, or in the decision to publish the results.

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