Journal of Agricultural Science; Vol. 16, No. 7; 2024
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Potential of Neem (*Azadirachta indica*) Extract in Managing Fall Armyworm on Maize

Tom Richard Okello[1], Cosmas Wacal[1,2], Wadria Denis Peter[1], Allan Obonyom Tekkara[3], Costa Gumisiriya[2] & John Patrick Kanahe Kagorora[2]

[1] Department of Agriculture and Natural Sciences, Faculty of Agriculture, Uganda Martyrs University, Kampala, Uganda

[2] Department of Crop and Animal Production, Faculty of Agriculture and Environmental Sciences, Mountains of the Moon University, Fort Portal City, Uganda

[3] Ngetta Zonal Agricultural Research Institute, National Agricultural Research Organization, Lira City, Uganda

Correspondence: Cosmas Wacal, Department of Crop and Animal Production, Faculty of Agriculture and Environmental Sciences, Mountains of the Moon University, P.O. Box 837, Fort Portal City, Uganda. Tel: 256-780-633-425. E-mail: cosmas.wacal@mmu.ac.ug

Received: April 6, 2024 Accepted: May 16, 2024 Online Published: June 15, 2024

doi:10.5539/jas.v16n7p114 URL: https://doi.org/10.5539/jas.v16n7p114

Abstract

This research assessed the effect of neem leaf extract on the larval population of the fall armyworm and the level of damage, growth, and yield of maize. A Randomized Complete Block Design (RCBD) with four treatments (Control, 50 g per L, 100 g per L and 200 g per L of neem leaf extract) applied within the two seasons of 2022A and 2022B. The findings showed that a higher concentration (200 g per L) of neem leaf extract-treated maize plants registered the least leaf damage (0.15), severity (0.15), and larvae population (0.1). This effect was most attained during the 1st season of maize production and at the earliest vegetative weeks of maize growth (3 WAP to 5 WAP, *i.e.*, weeks after planting). The higher neem leaf extract concentration of 200 g per L produced the most significant ($p < 0.001$) effect on maize growth traits. A higher plant height (162.51 cm), longer leaf length (112.5 cm), wider leaf width (11.7 cm), and broader stem girth (11.91 cm) were attained under 200 g per L of neem leaf extract treated plots during the 1st season of maize production and 11 WAP. The findings of this showed that a relatively high concentration of neem leaf extract produced a higher cob weight (200 g per L = 180.1 g) followed by 100 g per L (174.1 g), 50 g per L (140.9 g) and control (139 g). The weight was optimised during the 1st season of maize production (163.8 g). The grain yield was higher under 200 g per L (153.7 g) of neem extract. The above findings demonstrated that a high concentration of neem leaf extract reduced fall armyworm infestation and increased maize plant growth and yield. Farmers should, therefore, be encouraged to apply 200 g per L of neem leaf extract in the management of fall armyworms and improve plant growth and yield because it contains antifeedant and insecticidal properties against the fall armyworm.

Keywords: Azadirachtin, fall armyworm, grain yield, maize, neem leaf extract

1. Introduction

Maize *Zea mays* L. (Poaceae) is a nutritionally important food crop with much-needed nutrients for human and animal health (Arnarson, 2019). In Uganda, maize covers an average land area of 384,000 ha with yield annually 522,000 t, with a grain yield averaging 1.3 t per ha (MAAIF, 2018). However, despite these figures, the overall trend of production per unit area/or ha and yield during this period shows stagnation or decline, with maize growth primarily attributed to the expansion of cultivated areas rather than yield per unit area (Epule et al., 2021). The current trend of maize production is held back by several problems related to abiotic stress, such as erratic rainfall, poor/degraded soil quality, and biotic stress, such as pests and diseases contributing to poor yield (FAO, 2019a). It is widely accepted that this stress will become more acute due to climate change, resulting in a potential loss of up to 10% in maize production across Africa and Latin America by 2055 (Jones & Thornton, 2003).

Among the biotic stressors, the fall armyworm *Spodoptera frugiperda* (FAW) (J.E. Smith) (Lepidoptera: Noctuidae) emerges as the more serious, attacking maize plants at all stages of growth, from seedling, vegetative,

and flower to maturity stages (Bessin, 2018). Heavy infestation of fall armyworm on maize causes defoliation which eventually reduces the photosynthetic capacity of the affected plants (Matova et al., 2020). Additionally, the impact on yield is the greatest when the fall armyworm feeds on the tassels and cobs during pollination and grain filling (Baudron et al., 2019). Eggs are laid on plant foliage, and newly hatched larvae feed on the leaves, creating a windowing effect. Growing larvae prefer to hide in the whorl, damaging the developing leaves, which display a shot-hole pattern as they emerge (Supartha et al., 2021). In severe cases, the leaf may break off above the damaged area (Otim et al., 2020). For plants infested very early in the vegetative stage with few leaves present, FAW larvae hide in the soil at the base of the plant, where they can cause damage to the stem or kill the young plant (Otim et al., 2020). Given its widespread devastation, FAW has emerged as a major constraint to Maize production in Uganda (Kasoma et al., 2021). In addition, the cost of controlling this pest with recommended conventional inorganic pesticides proves expensive for many farmers (FAO, 2017; Andersson & Isgen, 2021). Moreover, using such pesticides is environmentally unfriendly/unsustainable, contributing to soil degradation, health risks to humans and animals, and ecosystem pollution (Ssemugabo et al., 2022). It is also evident that these chemicals come with complex specifications and instructions rarely understood by the users (Staudacher et al., 2020), which is attributed to illiteracy, complexity, and technicality of the language, signs, and symbols of these chemicals. Additionally, the abundance of adulterated and counterfeit chemicals further complicates the problem, fostering pest resistance and continuing economic losses in the region (Mundt et al., 2014). FAW cause economic losses to maize crops because they lower harvest qualities, and their control increases production costs in terms of buying the chemicals to control them (FAO, 2017). Also noted is that little information exists on sustainable management options to boost yield (Huyen et al., 2020).

In light of these challenges, it's quite evident that there is a need for sustainable options that mitigate the challenges arising from the use of synthetic pesticides. Neem *Azadirachta indica* A. Jussieu (Meliaceae) extract is a promising candidate, known for its bio-insecticidal properties derived from compounds like nimbin and Azadirachtin (Alzohairy, 2016). This natural solution offers an environmentally friendly, cost-effective alternative to conventional pesticides, with documented efficacy against fall armyworms (Faheem et al., 2014; Aniwanou et al., 2020). Moreover, neem's diverse applications extend beyond pest control, encompassing disease prevention, treatment, and plant stress tolerance enhancement (Islas et al., 2020). Earlier findings confirmed that neem and its constituents play a crucial role in the scavenging of free radical generation and prevention of disease pathogenesis due to present of nimbin which is a bio-insecticides that act by disrupting the growth and development of insects and by deterring their feeding (Alzohairy, 2016). In support to these findings, Kambrekar (2022) also noted that, the insecticidal activity of some parts of the neem tree is due to limonoids, mainly Azadirachtin A and B, Nimbin, Salannin and similar compounds. Though, a number of evidence point to Azadirachtin as being the more important active principle ingredient capable of repelling, deterring insect feeding, as well as inhibiting their growth and reproduction consequently reducing their population (Elteraifi & Hassanali, 2011; Alzohairy, 2016). Interestingly, Azadirachtin is not persistent in the environment, mainly because of rapid degradation by sunlight (Alzohairy, 2016). The chemistry, environmental behaviour and biological effects of neem products have been the subject of several reviews (Kilani-Morachi et al., 2021).

Several commercial formulations containing Azadirachtin A are now available on the world market for insect control in organic farming. However, in developing countries, high-cost formulations cannot be afforded and neem preparations (neem oil and water extracts) are commonly used as insecticides (Alzohairy, 2016). *Azadirachtin indica* seed extracts are used in cotton crops to control insects such as leafhoppers and whiteflies (Hemiptera) (Chaudhary et al., 2021). In Mali, the empirical technique used by Malian farmers to produce Azadirachtin-based insecticides is based on soaking 100 g seed kernels in 1L of water for 3 to 7 days to obtain an aqueous extract (Choupanian et al., 2017).

Despite existing literature emphasizing neem's potential, there is a need to conduct research to clarify and identify the most effective neem extract concentrations for mitigating the negative effects of FAW. Therefore, this research assesses the efficacy of neem extract in managing fall armyworm infestations in experimental maize fields under natural conditions and its impact on maize vegetative growth and yield in Ngetta Sub-County, Lira District, Uganda.

2. Method

2.1 Experimental Site

This research was performed in Ngetta Sub-County, Lira district, located in Northern Uganda. It is bordered by Pader District to the North, Otuke District to the Northeast, Alebtong District to the East, Dokolo District to the Southeast, Apac District to the Southwest and Kole District to the West (UCC, 2010). The coordinates of Lira

district headquarters are 2°14′50.0″S; 32°54′00.0″E (Latitude: 02.2472; Longitude: 32.9000). The district lies at an average elevation of 1,063 m (3,488 ft), above sea level.

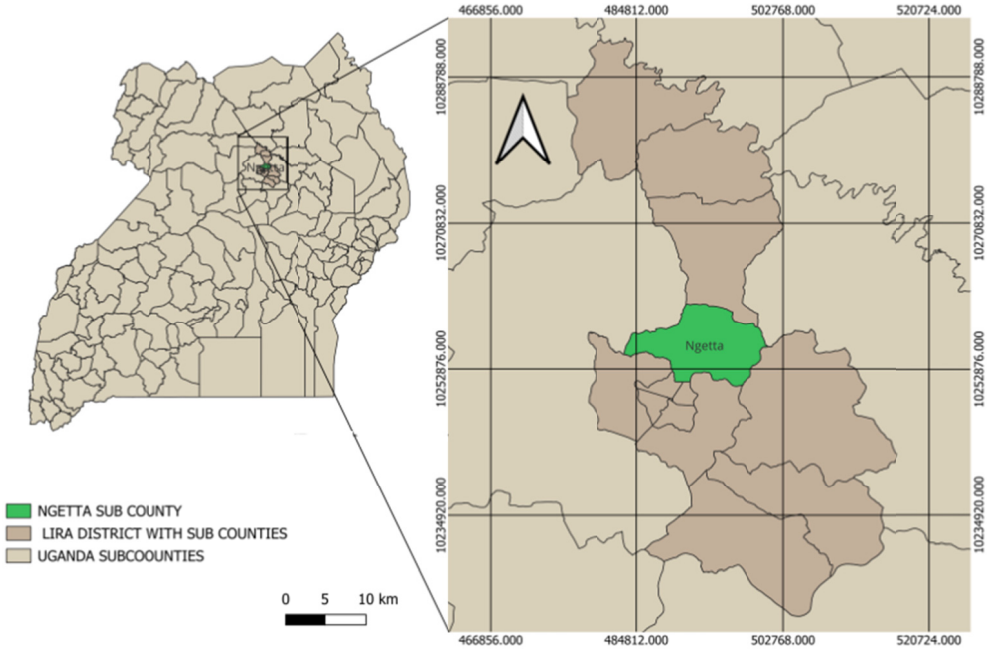


Figure 1. Map of the experimental site (Ngetta sub-county, Lira)

The rainfall in the district is bimodal, with one peak occurring during April-May and the other occurring in August-October. The average annual rainfall in the district varies between 1200-1600 mm, decreasing northwards. The rainfall is mainly convectional and comes typically in the afternoons and evenings. The average minimum and maximum temperatures are 22.5 °C and 25.5 °C, respectively. The absolute maximum temperature hardly goes beyond 36 °C, and the absolute minimum hardly falls below 20 °C. The month with the highest relative humidity is May (79.87%). The month with the lowest relative humidity is February (42.55%). Ferralsols and Leptosols with a sandy loam texture are the dominant soil types of Lira district and the topography is flat to gentle slopes (Byaruhanga & Kigoolo, 2005).

2.2 Experimental Design and Lay Out

A field experiment with maize was conducted in the first and second rainy seasons of 2022. The first season maize was planted on the 14th of March 2022 and harvested on the 9th of July 2022, while the second season was planted on the 4th of August 2022 and harvested on the 15th of December 2022. The experiment was arranged in a Randomized Complete Block Design (RCBD) consisting of four treatments which included; T1 = Control, T2 = 50 g per L, T3 = 100 g per L and T4 = 200 g per L of neem leaf extract. An experimental field measuring 15 × 15 m (225 m^2) in length and width was established. The experimental size of 3 × 3 m (9 m^2) length and width was divided into plots using a tape measure and with four replicates. A clear perimeter of 2 m was maintained around the experimental field to minimize cross-border interference and facilitate easy movement within and around the field for purposes of carrying out agronomic practices and data collection. Maize Variety (DH04) was planted at a spacing of 75 × 30 cm. Before planting, diammonium phosphate (N-P_2O_5-K_2O, 18:46:0) was applied at a recommended rate of 50 kg $acre^{-1}$ (22.5 kg N ha^{-1} and 57.5 kg P_2O_5 ha^{-1}), and urea applied at ten leaf stage at a rate of 50 kg $acre^{-1}$ 57.5 kg N ha^{-1} as top dressing). First and second weeding were properly carried out in the second and seventh week after sowing to make sure there was no competition for growth requirements. This was done by the use of hand hoe to suppress weed growth in the plots.

2.3 Preparation and Application of Neem Leaf Extract Treatments

2.3.1 Preparation of the Treatments

Neem extract was prepared by the method described by Calbiochem et al. (2015) and (The Fankaso Women Marketing Federation, 2020) with some modifications. Initial plant screening was carried out with pesticidal

plant species commonly known as Indian neem. The green leaves of the five-year old neem trees were collected from the homestead of some local farmers in the two villages of Okii-oyere and Te-got in Lira district. Leaves of the neem were washed by tap and distilled water subsequently and shade dried at room temperature for 30 days, pounded to a fine powder by a pestle and a locally made pounding mortar and kept in cool dark conditions until its time of application (Ngegba et al., 2022). The different concentrations of neem leaf extracts were formulated by measuring a known quantity of neem leaf powder and thoroughly mixed in a container of each 20 L of water containing 10 g piece of soap for 72 h at room temperature (Table 1). The extracts were then decanted three times using a 3 mm plastic sieve to produce a clear filtrate and used immediately in bioassays.

Table 1. The different formulations of neem leaf extracts.

Treatment	Neem leaf powder (kg)	Water (L)	Neem leaf extract concentration (g per L)
T1	0	20	0
T2	1	20	50
T3	2	20	100
T4	4	20	200

2.3.2 Treatment Application

The concoction obtained was then applied using a knapsack sprayer fitted with a flat fan nozzle type. Throughout the two seasons of maize production, only a single application was able to kill the larvae of the FAW, and all were applied during the 5th week of maize plant growth. The treatments were then applied for both the 1st (11th of April 2022) and 2nd (13th of July 2022) seasons of maize production. Solutions of different concentrations of the neem leaf extract were considered as treatments.

2.4 Determination of Pest Infestations, Level of Damage and Severity

FAW larvae population was estimated as follows. Each of the 10 sampled plants per plot was examined by looking for signs of fall armyworm eggs; feeding by small caterpillars, such as pinhole or windowpane leaf damage; droppings; ragged and torn leaves; and pupae in the soil (FAO, 2021). Focus was taken on the newest two or three leaves emerging from the funnel, as this is where caterpillars like to feed and where moths lay eggs. For later maize growth stages, the newest three or four leaves emerging from the funnel, plus the emerging tassel were examined. Counts of FAW larvae population were taken from each plant and plot of the different treatments. This was done throughout the 3rd, 5th, 7th, 9th and 11th week of maize growth.

The level of damage was expressed as shown below.

$$\text{Leaf damage (\%)} = \frac{\text{Total number of leaves damaged}}{\text{Total number of leaves per plant}} \times 100 \quad (1)$$

On the other hand, the level of severity on leaves was determined accordingly on a scale of (0-9) as described by Davis and Walliams (1992). According to this scale, a score of 0-4 indicated a low, 5-7 for medium and 8-9 for high.

2.5 Determination of Growth and Yield

2.5.1 Plant Height (cm)

Ground-truth height measurements were recorded manually using a meter stick to determine the height of each plant (Han et al., 2018). The plant height measurements were recorded at 3 WAP, 5 WAP, 7 WAP, 9 WAP and 11 WAP for both the first and second seasons, respectively.

2.5.2 Leaf Length and Width (cm)

Leaf length was measured on the third leaf using the tape measure from the lamina tip to the point of petiole intersection along the midrib. Leaf width was taken from the same plant and measured from the left margin of the leaf to the right margin at the exact midpoint of the leaf using the tape measure.

2.5.3 Stem Girth (cm)

Maize plant stem girth was measured with the aid of a tape measure from along the side of the plant to the base point of the center of the maize plant. The measurement was taken at a right (90°) angle to the trunk.

2.5.4 Grain Yield

The grain weight per plant was determined after harvesting and drying cobs to approximately 14% (the recommended moisture content). This involved separating the stalk leaf husks and shelling the cobs to obtain grain, which was measured to determine the individual plant grain weight (g). The overall grain weight per plot (kg) was thus obtained after threshing all the grain from the cobs obtained per plot (Mutungi et al., 2019).

2.6 Data Analysis

Data obtained on maize growth responses; plant height, leaf length, leaf width; Fall armyworm (*Spodoptera frugiperda*) larvae population and yield was subjected to three-way factor analysis of variance using GenStat 14 at 5%, 1% and 0.1% significance level to determine fisher's probability (F.pr), grand mean, least significant differences (L.S.D.) and co-efficient of variations (CV%).

3. Results and Discussions

3.1 Efficacy of Neem Extracts in Management of FAW in Maize Under Field Conditions

The effect of neem leaf extracts on management of FAW in maize under field conditions was determined within the different rates of treatment (T), season (S) of production and weeks (W) of plant growth. A three-factor analysis of variance was performed. The results in Table 2 shows that neem leaf extracts produced significant ($p < 0.001$) effect on leaf damage, fall armyworm severity and larvae population. This was significantly ($p < 0.001$) attained within the different rates of treatments (T), season (S) and week (W) of maize plant growth. Interaction of the treatment and season (TXS), treatment and weeks (TXW), seasons and weeks (SXW) and treatments, seasons and weeks (TXSXW) were significantly ($p < 0.001$) registered.

Table 2. Source of variation for the effect of neem leaf extract in the management of FAW in maize under field condition

Source of variation	d.f.	Leaf Damage	Severity	Larvae population
Treatment (T)	3	85.3***	317.97***	346.6***
Season(S)	1	168.4***	36***	129.96***
Week(W)	4	120.8***	457.3***	326.9***
TXS	3	68.6***	5.9**	48.2***
TXW	12	24.6***	75.2***	78.3***
SXW	4	41.7***	36.3***	61.5***
TXSXW	12	19.1***	13.2***	22.6***
Residual	1560	0.1	1.2	1.491

Note. *** Significant at 0.1%, ** Significant at 1%, * Significant at 5%, ns = non-significant, df = degrees of freedom, T = Treatment, S = Season, W = Weekend.

3.1.1 Leaf Damage

As shown in Table 3, maize leaf damage was significantly ($p < 0.001$) influenced by the different rates of neem extracts. With a high coefficient of variation (73.9%), the treatments produced a high effect on leaf damage. A 200 g/L of neem extract produced the most effect on fall armyworm leading to less damage on maize plant leaves. Merely 0.15 rate of leaf damage was attained compared to plots treated with 100 g/L (0.33), 50 g/L (0.38) and control (1.19). Consistently, leaf damage was significantly ($p < 0.001$) different within the period of maize growth. Leaf damage was more 3WAP (1.26) and 5WAP (1.09). The leaf damage was also significantly ($p < 0.001$) different within the seasons of maize production. Damage was highly experienced in the 2nd season of production compared to the 1st.

Table 3. Effect of neem extracts on leaf damaged by fall armyworm during growing seasons and weeks.

Treatment	Season	3 WAP	5 WAP	7 WAP	9 WAP	11 WAP	Mean (S)	Mean (T)
Control	Season 1	0.70	0.53	0.00	0	0	0.25	1.19
	Season 2	3.70	5.53	1.43	0	0	2.13	
50 g/L	Season 1	0.63	0.48	0.00	0	0	0.22	0.38
	Season 2	1.63	0.90	0.15	0	0	0.54	
100 g/L	Season 1	0.55	0.40	0.00	0	0	0.19	0.33
	Season 2	1.43	0.88	0.00	0	0	0.46	
200 g/L	Season 1	0.45	0.00	0.00	0	0	0.09	0.15
	Season 2	1.00	0.03	0.00	0	0	0.21	
	Mean(W)	1.26	1.09	0.20	0	0	0.51	0.51
Factor	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	
LSD	0.05237	0.03703	0.05855	0.07407	0.11711	0.08281	0.16562	
CV (%)	73.9							
SE	0.3776							

The variation in leaf plant damage was attributed to a number of factors. First, a high rate of neem concentration (200 g/L) treated plots produced the least damaged plants due to the availability of insecticidal properties; *Azadirachtin* which inhibited fall armyworm reproduction and disrupted the feeding pattern, causing a high mortality while a low rate produced relative damage as the effectiveness of the insecticidal properties reduced (Paredes-Sánchez et al., 2021). Consequently, damage was high at control because no neem extracts were present and no disruption of fall armyworm reproduction and feeding pattern was attained except for other factors such as natural enemies including lady bird and wasps. Secondly, the leaf damage declined in the 1st season of maize production to the 2nd due to the variation in weather conditions. The first season of maize production had stable rainfall patterns, which were a disruptive condition for the fall armyworm. Fall armyworm thrives most in warm conditions where reproduction and feeding are high; therefore, damage was experienced during the second season of maize production (Makgoba et al., 2021). Thirdly, leaf damage was very high, 3 WAP to 5 WAP, then 7 WAP to 11 WAP (Figure 2). This was consistent with the breeding pattern of fall armyworm, which was high during the earliest vegetative stage of maize growth, and within 14 days, the cycle evolved to a moth. Hence, leaf damage was not experienced.



(a) **(b)**

Figure 2. Assessing damaged plants (a), and heavily damaged maize plant (b)

3.1.2 Severity

The severity of fall armyworm in maize plants was determined using Davis and Walliams (1992) rating scale. Throughout the two seasons of production and period of maize growth, the level of fall armyworm severity was determined. Three-factor analysis was performed, and the results are presented in Table 4 below.

Table 4. Fall armyworm severity in maize plants

Treatment	Season	3 WAP	5 WAP	7 WAP	9 WAP	11 WAP	Mean (S)	Mean (T)
Control	Season 1	3.88	3.45	2.45	0.00	0.00	1.96	2.22
	Season 2	5.83	5.85	0.70	0.00	0.00	2.48	
50 g/L	Season 1	2.03	1.43	0.15	0.00	0.00	0.72	0.95
	Season 2	4.03	1.88	0.00	0.00	0.00	1.18	
100 g/L	Season 1	1.58	0.65	0.00	0.00	0.00	0.45	0.56
	Season 2	2.58	0.83	0.00	0.00	0.00	0.68	
200 g/L	Season 1	0.80	0.00	0.00	0.00	0.00	0.16	0.15
	Season 2	0.65	0.08	0.00	0.00	0.00	0.15	
	Mean(W)	2.67	1.77	0.41	0.00	0.00	0.97	0.97
Factor	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	0.002	<.001	<.001	<.001	
LSD	0.1528	0.108	0.1708	0.2161	0.3417	0.2416	0.4832	
CV (%)	113.6							
SE	1.1017							

The results show a significant ($p < 0.001$) difference in fall armyworm severity within the treatments. 200 g/L of neem concentrate produced the least affected maize plants with a severity level of 0.15 compared to 100 g/L (0.56), 50 g/L (0.95) and control (2.22). Similarly, the seasonality of maize production significantly ($p < 0.001$) influenced fall armyworm severity as high levels were experienced in season 2 compared to season 1. Severity levels were significantly ($p < 0.001$) different within the period of growth; severity was highly attained from 3 WAP to 7 WAP, while no severity or infestation was registered during the 9 WAP to the 11 WAP. The interaction of the treatments and season, treatments and week, season and week, and treatment, seasons and week produced a significant ($p < 0.001$) difference in fall armyworm severity in maize plants. 200 g/L neem-treated plants attained the lowest fall armyworm severity 5 WAP during the second season of maize production (0.08), while control attained the highest severity during the 2nd season of maize production (5.83). A very high coefficient of variation (113.6%) shows that a high rate of neem extract concentration produced the most effect in reducing fall armyworm severity in maize plants, while severity increased with a decline in neem concentration.

The above findings indicate that increasing neem leaf concentration in the management of fall armyworm reduced its severity in maize plants. Its reduction, however, increased severity. However, this was increased when warm conditions were available during the first season of maize production and when maize plants were still at early vegetative growth stage (Tulashie et al., 2021). In addition, the effectiveness of insecticidal properties increased when the concentration was increased (Helps et al., 2017). Neem is known to contain *nimbin* one of the insect repellents that interferes with the normal growth and development of fall armyworm and antifeedant properties that suppress the feeding sensation in insects at a concentration even less than 1 part per million (Giongo et al., 2016; Chaudhary et al., 2017).

3.1.3 Larvae Population

The results show that the larvae population was significantly ($p < 0.001$) different within the treatments. 200 g/L (0.1) of neem-treated plants registered the least number of larvae population compared to 100 g/L (0.38), 50 g/L (0.69), and control (2.19) (Table 5). The larvae population was also significantly ($p < 0.001$) higher during the second season of maize production than the first. Larvae population significantly ($p < 0.001$) increased within the period of maize growth. A high larvae population was observed 3 WAP (2.3) but declined from 5 WAP (1.5) to the 7 WAP (0.4). Consequently, no observation was registered from the 7 WAP for all treatments except for control plots till the 11 WAP. The larvae population was also significantly ($p < 0.001$) influenced by the interaction between the treatments and season, treatment and weeks, and treatment, seasons and weeks. Overall,

the larvae population increased in plots with the least neem concentration during warm weather conditions (season 1) and during vegetative growth of maize crops.

Table 5. Larvae population under different treatments, seasons and weeks

Treatment	Season	3 WAP	5 WAP	7 WAP	9 WAP	11 WAP	Mean (S)	Mean (T)
Control	Season 1	2.5	2.9	1.7	0.0	0.0	1.4	2.2
	Season 2	7.5	5.9	1.5	0.0	0.0	3.0	
50 g/L	Season 1	1.3	0.9	0.0	0.0	0.0	0.5	0.69
	Season 2	3.2	1.5	0.0	0.0	0.0	0.9	
100 g/L	Season 1	0.8	0.5	0.0	0.0	0.0	0.3	0.38
	Season 2	1.9	0.7	0.0	0.0	0.0	0.5	
200 g/L	Season 1	0.6	0.0	0.0	0.0	0.0	0.1	0.1
	Season 2	0.4	0.0	0.0	0.0	0.0	0.1	
	Mean (W)	2.3	1.5	0.4	0.0	0.0	0.8	
Factor	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	0.001	<.001	0.245	<.001	
LSD	0.1693	0.1197	0.1893	0.2395	0.3786	0.2677	0.5355	
CV (%)	144.9							
SE	1.2209							

The above findings demonstrate that the larvae population declined in plots with a high concentration of neem leaf extract and increased as the concentration declined in plots with no treatment, where the population was high. This effect was possible because a high concentration of neem leaf extract increased the availability of insecticidal and antifeedant properties (Sarawaneeyaruk et al., 2015; Shannag et al., 2015; Mondédji & Nyamador, 2019). Larvae population also increased within 3 WAP because the experiment coincided with the fall armyworm reproduction cycle. Besides, maize production was under normal field conditions; hence, plant growth was reliant on the available field conditions. However, fall armyworm larvae population was completely wiped out throughout the 7 WAP till 11 WAP due to the end of the larvae cycle of moth but also due to the cannibalistic nature of the fall armyworm when there is overpopulation. These findings were consistent with Baudron et al. (2019) and Supartha et al. (2021), who made a similar observation and reported that fall armyworm takes 14 days to transform from the most disastrous stage on plants of larvae to a pupa; therefore after those 14 days, the infestation declines and other factors may therefore affect the plant growth.

3.2 Effects of Neem Extract on Vegetative Growth of Maize

Furthermore, results show that maize plant height (cm), leaf length (cm), leaf width (cm), and stem girth (cm) were significantly ($p < 0.001$) different within the different treatments, seasons, and weeks of maize plant growth (Table 6). Similarly significant ($p < 0.001$) differences were produced by the interactions between treatments and seasons, treatment and weeks, and season and weeks.

Table 6. Source of variation

Source of variation	d.f.	Plant Height (cm)	Leaf Length (cm)	Leaf Width (cm)	Stem Girth (cm)
Treatment	3	44063.1***	32791.33***	867.43***	326.37***
Season	1	121575.8***	94527.01***	797.46***	811.87***
Week	4	336826.5***	80623.97***	878.84***	698.33***
Treatment × Season	3	896.8***	451.4***	4.25***	0.255ns
Treatment × Week	12	528.6***	777.32***	13.21***	5.87***
Season × Week	4	6912.5***	1165.32***	1.088ns	19.18***
Treatment × Season × Week	12	462.4***	290.74***	2.79***	2.59***
Residual	1560	117.7	58.58	0.80	0.7232

Note. *** Significant at 0.1%, ** Significant at 1%, * Significant at 5%, ns = non-significant, df = degrees of freedom.

These outcomes demonstrate that neem leaf extract can be moderated by existing field conditions and the growth pattern of the crop. The subsequent sections present an independent analysis of the effect of neem leaf extract on maize plant height, leaf length, leaf width, and stem girth.

3.2.1 Plant Height

Results also show that maize plant height was significantly ($p < 0.001$) influenced by the different concentrations of neem leaf extract. A 200 g/L treated plant attained the highest plant heights (99.2 cm) compared to 100 g/L (91.6 cm), 50 g/L (84.86 cm), and control (74.5 cm) (Table 7).

Table 7. Maize plant height (cm) growth under different treatments, seasons and weeks

Treatment	Season	3WAP	5WAP	7WAP	9WAP	11WAP	Mean (S)	Mean (T)
Control	Season 1	51.21	60.63	68.82	99.74	142.24	84.528	74.489
	Season 2	40.96	47.29	50.24	72.81	110.95	64.45	
50 g/L	Season 1	63.01	70.31	77.58	107.95	151.8	94.13	84.863
	Season 2	45.67	55.54	64.39	93.98	118.4	75.596	
100 g/L	Season 1	66.85	77	85.28	116.99	156.81	100.586	91.594
	Season 2	53.26	60.83	72.48	104.12	122.32	82.602	
200 g/L	Season 1	72.89	80.49	90.32	122.77	162.51	105.796	99.225
	Season 2	70.7	74.86	76.77	114.18	126.76	92.654	
	Mean(W)	58.1	65.9	73.2	104.1	136.5	87.5	87.5
	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	
LSD	1.505	1.064	1.682	2.128	3.365	2.379	4.759	
CV (%)	12.4							
SE	10.849							

Maize plant height was also significantly ($p < 0.001$) influenced by the production seasons. Maize plants under cultivation in the 1st season attained the highest maize plants compared to the 2nd season. Significant ($p < 0.001$) variation in plant height was also registered within the weeks of plant growth. Maize plants were higher or taller at 11 WAP (136.5 cm) and shorter at 3 WAP (58.1 cm). Subsequently, maize plant height increased as the period of growth increased. Additionally, significant ($p < 0.001$) interaction between treatment and season, treatment and weeks, and season and weeks produced higher maize Plants. It was observed that maize plants' height was optimum under 200 g/L treated plots during the 11WAP and 1st season of production (162.51 cm).

In general, maize plant height was maximized under the highest concentration of neem leaf extract (200 g/L) within the 1st season of production and when the maize plants had reached maturity. This could be attributed to the potential nutrients provided by the neem leaf extract which may include NPK essential for maize growth and pest control. This high growth could also be linked to the favourable weather conditions present in the 1st season of maize production. This first season was characterized by high rainfalls, humidity, and average temperatures essential for the breakdown of plant macronutrients and trace elements from the soils/manures, available sunlight that aided the process of photosynthesis, and a well-established root system that supported the absorption of water and minerals essential for plant growth hence higher plants. These findings were consistent with research carried out by Ayito et al. (2018) which showed that crushed neem leaves contain adequate quantity of plant essential elements of 99.9% NPK and 0.01% micro-nutrients, C/N ratio of 4.14, which is less than 25 separating indices indicating that the rate of mineralization is high therefore minerals such as Phosphorous is vital for the growth of roots and fruit development, Potassium helps with flowering and general growth and Nitrogen is responsible for the continuous growth of foliage.

3.2.2 Leaf Length (cm)

In terms of leaf length, results show a significant ($p < 0.001$) difference in leaf length within the treatments. 200 g/L treated plants produced the longest leaf length (82.6 cm) compared to 100 g/L (74.4 cm), 50 g/L (69.7 cm) and control (61.0 cm) (Table 8). Leaf length was also significantly ($p < 0.001$) different within the seasons. Maize crops cultivated during the 1st season produced the longest leaves compared to the 2nd season. Similarly, leaf length was significantly ($p < 0.001$) influenced by the period of plant growth. By 11 WAP (93 cm), longer

leaf length was registered. A significant ($p < 0.001$) interaction of treatments, season and weeks produced significant ($p < 0.001$) difference in leaf width. Optimum leaf length was attained under 200 g/L treated plots during the second season and 11 WAP (112.5 cm).

Table 8. Maize leaf length (cm) growth under different treatments, seasons and weeks

Treatment	Season	3 WAP	5 WAP	7 WAP	9 WAP	11 WAP	Mean (S)	Mean (T)
Control	Season 1	48.39	56.93	66.08	77.4	99.35	69.63	61.0
	Season 2	36.77	44.41	47.58	54.18	78.49	52.286	
50 g/L	Season 1	56.62	66.64	75.71	88.57	100.03	77.514	69.7
	Season 2	41.33	51.98	64.35	72.63	79.03	61.864	
100 g/L	Season 1	64.28	71.89	80.67	91.55	103.74	82.426	74.4
	Season 2	47.1	56.08	68.57	77.82	81.95	66.304	
200 g/L	Season 1	68.42	77.25	87.15	98.78	112.5	88.82	82.6
	Season 2	56.79	72.62	74.08	89.89	88.88	76.452	
	Mean(W)	52.5	62.2	70.5	81.4	93.0	71.9	71.9
Factor	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	
LSD	1.062	0.751	1.187	1.501	2.374	1.678	3.357	
CV (%)	10.6							
SE	7.654							

The above results show that a higher concentration of neem leaf extract produced longer leaves. This was highly maximized when the maize plants attained maturity during favorable field conditions. A higher concentration of neem leaf produced the highest effect on maize leaf length due to the presence of relevant nutrients, including nitrogen (N), phosphorous (P), and potassium (K), which were essential for growth and avoiding of pests against plant infestation (Rakibuzzaman et al., 2019). Under favorable field conditions, reliable rainfall, humidity, and temperature, the breakdown of plant nutrients was easily achieved, and with a developed root and shoot system, maximum absorption of plant nutrients was maximized by the maize plants hence longer leaves.

3.2.3 Leaf Width (cm)

As shown in Table 9, a high coefficient of variation (11.6%) suggests that leaf width was significantly ($p < 0.001$) different within the treatments, seasons, weeks, and between the treatments, seasons, and weeks. Specifically, maize leaf width was significantly ($p < 0.001$) different within the treatments. Wider leaves were attained with 200 g/L (9.7 cm) compared to 100 g/L (7.9 cm), 50 g/L (6.9 cm) and control (6.3 cm). Leaf width was not significantly ($p > 0.05$) different within the production seasons. Leaf width was, however, significantly ($p < 0.001$) different within the period of maize vegetative growth. Wider leaves attained 11 WAP (9.5 cm), while narrow leaves attained 3 WAP (5.4 cm). However, there was a significant ($p < 0.001$) increase in leaf width throughout the 5 WAP (6.8 cm), 7 WAP (7.8 cm), and 9 WAP (8.9 cm). Additionally, a significant ($p < 0.001$) interaction between treatments, seasons, and weeks produced broader leaves under 200 g/L, 9 WAP (11.7cm) during the 1st season of maize production.

Table 9. Maize leaf width (cm) growth under different treatments, seasons and weeks

Treatment	Season	3 WAP	5 WAP	7 WAP	9 WAP	11 WAP	Mean (S)	Mean (T)
Control	Season 1	4.8	6.0	7.0	8.2	9.3	7.1	6.3
	Season 2	3.8	4.5	5.2	6.4	8.1	5.6	
50 g/L	Season 1	5.5	6.6	7.6	8.8	9.6	7.6	6.9
	Season 2	4.1	4.9	6.2	6.9	8.3	6.1	
100 g/L	Season 1	6.2	8.0	9.0	10.1	10.1	8.7	7.9
	Season 2	4.7	6.0	7.7	8.5	8.8	7.1	
200 g/L	Season 1	7.5	9.6	10.6	11.7	11.7	10.2	9.7
	Season 2	6.4	9.1	9.0	10.9	10.2	9.1	
	Mean(W)	5.4	6.8	7.8	8.9	9.5	7.7	7.7
Factor	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	0.001	<.001	0.245	<.001	
LSD	0.124	0.088	0.139	0.175	0.277	0.196	0.392	
CV (%)	11.6							
SE	0.8942							

The above findings demonstrate that a higher concentration of neem leaf positively and highly influenced maize leaf width. It was also optimized when maize plants had developed stronger root and shoot systems which maximized absorption of plant nutrients (osmosis) and manufacture of plant food (photosynthesis) when suitable weather conditions were attained during the 1st season of production. A higher concentration of neem leaf extract therefore has available plant nutrients (NPK) that improved vegetative growth of the maize crops. These findings were consistent with Mustapha et al. (2022), who found that a sole application of neem extract rapidly enhanced vegetative maize plant growth resulting from the adequacy of nitrogen. Nitrogen has been highlighted as a building block of plant life; plants that attain more of it register better growth (Alzohairy, 2016; Doshi et al., 2022).

3.2.4 Stem Girth (cm)

The results in Table 10 show that stem girth was significantly ($p < 0.001$) influenced by the different concentrations of neem leaf extract treatments. Plants under 200 g/L treatments attained the broadest stem girth (9.03 cm) compared to 100 g/L (7.7 cm), 50 g/L (7.4 cm), and control (6.94 cm). Within the seasons, no significant ($p > 0.05$) difference was attained in stem girth but the broadest in the 1st and 2nd seasons. The variation continued to be significantly ($p < 0.001$) registered within the vegetative to maturity stages of maize. It was observed that stem girth increased from 5.78 cm (3 WAP) to 9.39 cm (11 WAP). However, the interaction of treatments, season, and weeks significantly ($p < 0.001$) produced the broadest stem girth (11.91 cm) under the highest neem extract concentration (200 g/L), 11 WAP, and during the 1st season of production.

Table 10. Maize stem girth (cm) under different treatments, seasons and weeks

Treatment	Season	3 WAP	5 WAP	7 WAP	9 WAP	11 WAP	Mean (S)	Mean (T)
Control	Season 1	4.70	7.16	8.21	9.12	9.12	7.66	6.9372
	Season 2	4.23	5.30	6.40	7.57	7.57	6.21	
50 g/L	Season 1	5.82	7.35	8.28	9.34	9.62	8.08	7.3749
	Season 2	5.30	5.44	6.87	7.75	7.98	6.67	
100 g/L	Season 1	6.22	7.53	8.62	9.63	10.41	8.48	7.7425
	Season 2	5.66	5.57	7.16	7.99	8.64	7.00	
200 g/L	Season 1	7.48	8.58	9.79	10.83	11.91	9.71	9.0339
	Season 2	6.81	7.98	8.12	8.99	9.88	8.35	
	Mean(W)	5.78	6.86	7.93	8.90	9.39	7.77	7.77
Factor	T	S	W	TXS	TXW	SXW	TXSXW	
P-Value	<.001	<.001	<.001	0.001	<.001	0.245	<.001	
LSD	0.1179	0.083	0.132	0.167	0.2637	0.1865	0.373	
CV (%)	10.9							
SE	0.8504							

The above findings also highlight that a high concentration (200 g/L) of neem leaf extract produced the most effect on stem girth under favourable weather conditions in 1st season of production and when plants had attained optimum vegetative growth and root system development. The effect of neem leaf concentration was probably due to the availability of plant nutrients (NPK) in neem leaves which therefore aid plant growth hence broader stem girth. These findings were in agreement with Lokanadhan et al. (2012) and Moyin-Jesu (2010), who also observed that neem extracts produced the optimum stem girth in maize plants. This is so because neem has gained prominence for possessing the most vital nutrients (NPK) and trace elements required to boost plant growth rate, hence broader stem girth.

3.3 Effect of Neem Extracts on Maize Yield

3.3.1 Cob Weight (g)

Table 11 shows the outcome of different neem leaf extract treatments on maize yield during the two seasons of maize production.

Table 11. Cob weight (g)

Treatment	Season 1	Season 2	Mean (T)
Control	132.5	145.4	139.0
50g/L	145.8	136.0	140.9
100g/L	188.7	171.5	180.1
200g/L	188.2	160.0	174.1
Mean (S)	163.8	153.2	158.5
Factor	T	S	TXS
P-value	0.049	<.001	0.049
LSD	10.52	14.87	21.03
s.e.d.	5.35	7.56	10.69
CV (%)	30.2		

The results show that cob weight was significantly ($p < 0.05$) different within the treatments. Heavier cobs were attained under 100 g/L treated plants (158.5 g) compared to 200 g/L (174.1 g), 50 g/L (140.9 g) and control (139 g). Similarly, heavier cobs were significantly ($p < 0.001$) attained in 1st season (163.8 g) than 2nd season (153.2 g). The interaction of treatments and season also produced significantly ($p < 0.05$) heavier cobs. Heavier maize cobs were registered under 100 g/L (188.7 g) during the 1st season of maize production. The cob weight was higher under 100 g/L due to optimal plant nutrients; hence any addition could not affect any further growth significantly, while the plants produced in 1st season gained higher cob weight due to the adequacy of the nutrients which aided earlier and complete formation of the cobs This was in line with Ano and Agwu (2015) who argued that neem extract had the potential to increase yield in maize because it is rich in especially, Nitrogen and Phosphorus and some trace elements such as boron (B), magnesium (Mg), calcium (Ca) essential for the formation of cobs and grain in maize, hence a high concentration of the extract boost cob and seed formation. Additionally, Neem extracts contained Phytochemical properties, which repelled and contributed to the mortality of pests, which affect plant growth and yield (Doshi et al., 2022). Lokanadhan et al. (2012) also pointed out that *Azadirachta indica* used in the form of leaf extracts, seeds, cakes, oil, and fruit extracts has insecticidal, antifeedant, hormonal, antifungal, antiviral, and nematocidal properties.

3.3.2 Grain Weight (g)

As shown in Table 12, grain weight was significantly ($p < 0.001$) different within the treatments. Plants under 200g/l neem leaf concentrate produced higher grain weight (153.7 g) compared to 100 g/L (145.6 g), 50 g/L (119.5 g) and control (102.6 g). Similarly, grain weight was significantly ($p < 0.001$) influenced by the season. High grain weight was attained in 1st season (151.98 g) than 2nd season (108.73 g). The interaction of treatment and season significantly ($p < 0.001$) influenced grain weight. Maximum grain weight was attained under 200 g/L during the 1st season (195.2 g) of maize production.

Table 12. Grain weight (g)

Treatment	Season 1	Season 2	Mean (T)
Control	100.6	104.6	102.6
50g/L	141	98	119.5
100g/L	171.1	120.1	145.6
200g/L	195.2	112.2	153.7
Mean(S)	151.98	108.73	130.35
Factor	T	S	TXS
P-value	<.001	<.001	<.001
LSD	7.09	10.03	14.18
s.e.d.	3.6	5.1	7.21
CV(%)	24.7		

This outcome can be explained by the availability of plant nutrients in highly concentrated neem leaf extract and favorable weather conditions during the 1st season of production, which improved growth and yield. These findings were consistent with Verma et al. (2017) who also determined that Neem had a significant effect on nutrient uptake, leading to early growth, yield, and tolerance to pests and diseases. Ali et al. (2020) and Moyin-Jesu (2014) also reported that neem is composed of Phosphorus, Potassium, and Calcium efficiency, which leads to an enhanced grain yield.

4. Conclusion

In conclusion, a high rate of concentration of neem leaf extract (200 g/L) produced a positive effect on fall armyworm control or management. The high concentration reduced the level of infestation due to the availability of insecticidal and antifeedant properties, which inhibited fall armyworm reproduction and maize crop damage. Due to low fall armyworm infestation, the maize plants exercise maximum growth rate, leading to high yield. However, a low rate reduced efficacy and increased infestation, while non-application caused severe maize plant damage, leading to poor plant growth and yield. The study recommends the adoption of 200 g/L of neem leaf concentrate in the management of fall armyworm during maize production. This high rate of treatment has proven potent for the survival of fall armyworm. The study recommends for farmers to be trained on the application of neem leaf concentrate in the management of fall armyworm and other pests or insects. For further research, this study recommends an investigation on cost-benefit analysis of organic and bio-rationals in the costs of maize pest management.

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Acknowledgments

The authors are grateful to the administration of Ngetta Zonal Agricultural Research Institute, National Agricultural Research Organization, for hosting this research on their station.

Authors Contributions

Tom Richard Okello and Cosmas Wacal conceived the idea; Tom Richard Okello, Cosmas Wacal and Wadria Denis Peter performed the experiment, collected and analyzed the data; Cosmas Wacal, Allan Obonyom Tekkara, Costa Gumisiriya and John Patrick Kagorora interpreted the data; Cosmas Wacal and Tom Richard Okello wrote the manuscript and shared the first draft. All authors discussed the results and contributed to the final manuscript.

Funding

Not applicable.

Competing Interests

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.

Informed Consent

Obtained.

Ethics Approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and Peer Review

Not commissioned; externally double-blind peer reviewed.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data Sharing Statement

No additional data are available.

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