African Crop Science Journal, Vol. 34, No. 3, pp. 611 - 628
pISSN 1021-9730/2026
eISSN 2072-6589/2026

DOI: https://dx.doi.org/10.4314/acsj.v34i3.13

NEEM LEAF MULCH FOR INTEGRATED MANAGEMENT OF SOIL FERTILITY, FALL ARMYWORM AND WEED CONTROL FOR MAIZE PRODUCTION IN NIGERIA

PAILLAGE DE FEUILLES DE NEEM POUR LA GESTION INTÉGRÉE DE LA FERTILITÉ DU SOL, DE LA CHENILLE LÉGIONNAIRE D'AUTOMNE ET LE CONTRÔLE DES ADVENTICES DANS LA PRODUCTION DE MAÏS AU NIGERIA

S.U. EWANSIHA, F. AIYINOMWAN, E.N. OKAFOR, A. OSARETIN, J.O. OSAGIE and A.Y. KAMARA[1]

Department of Crop Science, Faculty of Agriculture, University of Benin, PMB 1154, Benin City, Nigeria
[1]Systems Agronomy Unit, International Institute of Tropical Agriculture, Kano Station, PMB 3112, Kano, Nigeria
Corresponding author: sylvester.ewansiha@uniben.edu

(*Received 8 April 2026; accepted 5 May 2026*)

ABSTRACT

Maize (*Zea mays* L.) production in sub-Saharan Africa (SSA) is constrained by many biophysical phenomena, particularly declining soil fertility, insect pests, and weed pressure. This study evaluated the integrative effects of neem (*Azadirachta indica*) leaf mulch (NLM) on soil fertility, fall armyworm (FAW) damage and weed suppression, for maize production in the tropical Rainforest Zone of Nigeria. A field experiment was conducted at the University of Benin Teaching and Research Farm, using four mulch rates (0, 1, 3 and 5 kg m^{-2}) arranged in a randomised complete block design, with four replicates. Fresh green Neem leaves were applied as surface mulch at sowing, 2 and 4 weeks after sowing (WAS). Results showed that NLM significantly improved soil organic carbon (27.1 to 103.5%), total nitrogen (10.5 to 33.3%), and available phosphorus (36.5 to 79.2%), relative to the control; while potassium response was minimal and variable. FAW damage was significantly reduced from 6 WAS onwards, with severity declining by more than 60% under mulched treatments. Weed density and biomass decreased substantially by 32.7 - 76.1% and 28.7 - 74.9%, respectively, with increasing mulch rates. Grain yield also increased significantly from 1.17 t ha^{-1} in the control to 4.13 t ha^{-1} at 5 kg m^{-2}; representing up to 252.8% improvement. Yield was negatively correlated with FAW damage and weed biomass; but positively associated with yield components. The study demonstrates that neem leaf mulch is an effective option for integrated management of soil fertility, FAW, and weeds in maize production. The 3 kg m^{-2} rate provided a near optimal balance between performance and resource use. Further studies should assess long-term impacts and scalability of the innovation across agro-ecological zones.

Key Words: Fall armyworm, green mulch, *Zea mays*

RÉSUMÉ

La production de maïs (*Zea mays* L.) en Afrique subsaharienne (ASS) est limitée par de nombreux phénomènes biophysiques, notamment la baisse de la fertilité des sols, les insectes ravageurs et la pression des adventices. Cette étude a évalué les effets intégrés du paillis de feuilles de neem (*Azadirachta indica*) (NLM) sur la fertilité du sol, les dégâts de la chenille légionnaire d'automne (FAW) et la suppression des adventices pour la production de maïs dans la zone de forêt tropicale humide du Nigeria. Une expérience de terrain a été menée à la ferme d'enseignement et de recherche de l'Université de Benin, en utilisant quatre doses de paillis (0, 1, 3 et 5 kg m^{-2}) disposées en blocs complets randomisés avec quatre répétitions. Des feuilles vertes fraîches de neem ont été appliquées en paillage de surface au semis, puis à 2 et 4 semaines après le semis (WAS). Les résultats ont montré que le NLM a significativement amélioré le carbone organique du sol (27,1 à 103,5 %), l'azote total (10,5 à 33,3 %) et le phosphore disponible (36,5 à 79,2 %) par rapport au témoin, tandis que la réponse du potassium est restée minimale et variable. Les dégâts de la FAW ont été significativement réduits à partir de 6 WAS, la sévérité diminuant de plus de 60 % sous les traitements paillés. La densité et la biomasse des adventices ont considérablement diminué (respectivement de 32,7 - 76,1 % et 28,7 - 74,9 %) avec l'augmentation des doses de paillis. Le rendement en grains a également augmenté de manière significative, passant de 1,17 t ha^{-1} pour le témoin à 4,13 t ha^{-1} à la dose de 5 kg m^{-2}, soit une amélioration allant jusqu'à 252,8 %. Le rendement était négativement corrélé avec les dégâts de la FAW et la biomasse des adventices, mais positivement associé aux composantes du rendement. L'étude démontre que le paillis de feuilles de neem est une option efficace pour la gestion intégrée de la fertilité du sol, de la FAW et des adventices dans la production de maïs. La dose de 3 kg m^{-2} a offert un équilibre presque optimal entre performance et utilisation des ressources. Des études ultérieures devraient évaluer les impacts à long terme et l'extrapolabilité de cette innovation à travers d'autres zones agroécologiques.

Mots Clés : Chenille légionnaire d'automne, paillis vert, *Zea mays*

INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereal crops in sub-Saharan Africa (SSA), owing to its diverse uses as food for humans, feed for livestock and raw material for various agro-industrial processes. The crop is adaptable across different agro-ecological zones and is predominantly produced by smallholder farmers under rain-fed conditions (Badu-Apraku and Fakorede, 2017). The high adaptability of the crop to a wide range of climatic and soil conditions, coupled with its high yield potential, have contributed to its increasing significance among staple cereals in the region (FAO, 2023).

Unfortunately, owing to decline in soil fertility, and pressure of pests and diseases, maize productivity has persistently declined in the region, to levels as low as 1.69 t ha^{-1}, compared with global averages of 5-6 t ha^{-1} (IITA, 2022; Ewansiha *et al.*, 2023; FAO, 2023). The soils are reportedly low particularly in nitrogen, phosphorus and potassium; the macronutrients responsible for biggest proportion of crop yields (Bender *et al.*, 2013; Fathi, 2022). Use of soil fertility replenishing inputs has been low in SSA, owing to the costs associated; and complexities of using mostly agro-chemicals, which are associated with environmental ill-health.

On the other hand, biotic stresses, particularly the fall armyworm (*Spodoptera frugiperda* J.E. Smith), further reduce maize productivity. This invasive pest, now widespread in SSA, feeds preferentially on cereals, attacking seedlings through to maturity (Montezano *et al.*, 2018; Kelita *et al.*, 2020). Defoliation and ear feeding reduce photosynthetic capacity and grain filling, causing 21-53% yield losses or, in severe cases, total crop failure (Matova *et al.*, 2020;

Otim *et al*., 2020). Synthetic insecticides are commonly used to control the pest, but are prone to misuse, environmental contamination and development of pest resistance (Yu, 1991; Pearsall and Hogue, 2000).

Weeds infestation is the other major constraint to viable maize production in the SSA (Benjamin *et al*, 2024). Weeds exert stiff competition with the crop for essential resources, including light, nutrients and water; while some weed species also act as alternative hosts for pests and pathogens that can further reduce crop productivity (Deewan *et al*., 2017; Ramesh *et al*., 2017; Singh *et al*., 2021). Weed interference is widely recognised as the most significant biological constraint to maize production, with global scores of yield losses of up to 37%, in the absence of effective control measures (Dereje *et al*., 2018; Gharde *et al*., 2018). Use of herbicides, though reportedly effective, has not been leveraged widely in SSA, largely owing to unaffordable costs and their extensive and indiscriminate negative environmental concerns. Reports are awash with contamination of soil and water resources, harmful effects on non-target organisms, biodiversity loss, and the development of herbicide-resistant weed populations (Travlos *et al*., 2020; Zaller, 2020; Parven *et al*., 2025).

Organic mulching has been widely recognised as an effective strategy for improving soil health, conserving moisture, suppressing weeds, and enhancing crop productivity (Rossi *et al.*, 2024). Organic mulches improve soil structure, increase soil organic carbon, and enhance water retention (Lal, 2004; Rossi *et al.*, 2024). Mulching also moderates soil temperature and reduces evaporation losses, thereby creating a favourable microenvironment for crop growth (Teasdale and Mohler, 2000). In addition, mulch acts as a physical barrier that suppresses weed emergence, by limiting light penetration and reducing weed seed germination (Khamare and Marble, 2023; Teasdale and Mohler, 2000). Empirical studies have further demonstrated that organic mulching can significantly improve crop yield through enhanced soil moisture conservation and reduced weed competition (Singh and Chamroy, 2025).

Beyond soil and weed management, organic mulches play a vital role in enhancing soil biological activity. Mulching promotes beneficial microbial populations that contribute to nutrient cycling and suppress soil-borne pathogens. The gradual decomposition of organic residues releases essential nutrients such as nitrogen, phosphorus, and potassium; thereby improving soil fertility and long-term productivity (Lal, 2004). However, most existing studies have focused on the general effects of organic mulches, with limited emphasis on the integrated use of specific plant materials capable of addressing multiple agronomic constraints simultaneously.

Neem has attracted considerable attention due to its multifunctional properties in agriculture. The tree, *A. indica,* is widely distributed across West Africa and other tropical regions, making it a readily available and low-cost resource for farmers. Neem contains bioactive compounds such as azadirachtin, which exhibit insecticidal, antifeedant, growth-regulating, and repellent effects against a wide range of insect pests (Isman, 2006). These properties make neem particularly promising for the management of Fall armyworm (FAW), whose control using conventional pesticides has become increasingly challenging due to resistance and environmental concerns (Isman, 2006; Day *et al*., 2017).

In addition to its pesticidal properties, neem leaves contribute organic matter and nutrients to the soil upon decomposition, thereby further enhancing soil fertility (Gajalakshmi and Abbasi, 2004). Neem residues have also been reported to exhibit allelopathic effects that can suppress weed growth and reduce weed pressure in cropping systems (Xuan *et al*., 2004). These combined properties suggest that neem leaf mulch could serve as a multifunctional agricultural input, concurrently acting as a bio-fertiliser, bio-herbicide and bioinsecticide; thereby enhancing maize yield, while mitigating the ecological risks associated with synthetic agrochemicals (Ewansiha *et al*., 2023). Given the increasing demand for climate-smart, eco-friendly, and cost-effective agricultural practices, the objective of this study was designed to establish the integrative effect of neem (*Azadirachta indica*) leaf mulch residues on soil fertility, fall armyworm (FAW) and weeds infestation in maize production in Nigeria.

MATERIALS AND METHODS

Experimental site. A field experiment was conducted at the Teaching and Research Farm of the Faculty of Agriculture, University of Benin, Benin City (06º 20 'N, 5º 37'E; 78 m asl.); located in tropical Rainforest of Nigeria, during the early cropping season and repeated in the late cropping season of 2024. Site soil is classified as Ultisol (Umweni *et al*., 2014); while rainfall is of high intensity and bimodal, beginning in March/April and ending in October/November, with a dry short spell in August usually referred to as "August Break". Approximately 2025 mm of precipitation falls annually in Benin City, with an average annual temperature of 26.1 °C (Climate-Data.org, 2016).

The zone has a total growing period of 211 to 270 days (Ogeh and Ukodo, 2012). The period from the commencement of rain to the time of "August Break" is commonly regarded as early cropping season; whereas the period from the break in August to the end of rains is regarded as the late cropping/growing season. Both seasons are favourable for the production of maize. The rainfall and mean monthly temperature data for the period of experimentation are shown in Figure 1. Prior to field experimentation, the field was under fallow for two years, and was predominantly covered by Guinea grass (*Panicum maximum* Jack).

Treatments and design. Treatments consisted of four rates of fresh green *Azadirachta indica* leaf residues (0, 1, 3, 5 kg m^{-2}) applied as mulch. Fresh green leaves of neem, obtained from trees serving as wind breaks around the Teaching and Research Farm, were used in the experiment. The freshly cut *A. indica* leaves, were weighed soon after cutting and applied at sowing, 2 and 4 WAS as mulch. One third of each treatment rate was applied at each time of application on the entire surface of each plot, without incorporation of the neem leaves.

The experiment was laid out in a randomised complete block design, replicated four times and repeated for two seasons. Each treatment plot measured 2.25 m x 2.0 m, with 0.75 m wide alleyways between plots and blocks.

Maize cultivar used. The open pollinated maize cultivar, Sammaz 52, was the test crop used in this study. Seeds were obtained from Premier Seed Company Ltd, Zaria, in Nigeria. This cultivar matures in 110-120 days, consists of intermediate levels of pro-vitamin A content, and is tolerant to maize streak virus, rust, leaf blight and Auricularia leaf spot (Nigeria Seed Portal Initiative, 2026). It yields up to 6 t ha^{-1} in Northern Guinea savanna.

Agronomic practices. Land was cleared manually using cutlass and the debris removed from the field without burning. Two seeds were sown, 4-5 cm deep in a moist soil at a spacing of 75 cm x 25 cm. Seedlings were thinned to one plant per stand two weeks after sowing (WAS), to achieve a plant population of 53,333 plants ha^{-1}. Hand-pulling was done with limited hand-hoeing at 3 and 5 WAS, outside the established quadrants in each plot.

Neem leaf and soil analysis. Prior to field application of the neem leaves, composite samples of the leaves were dried, ground and

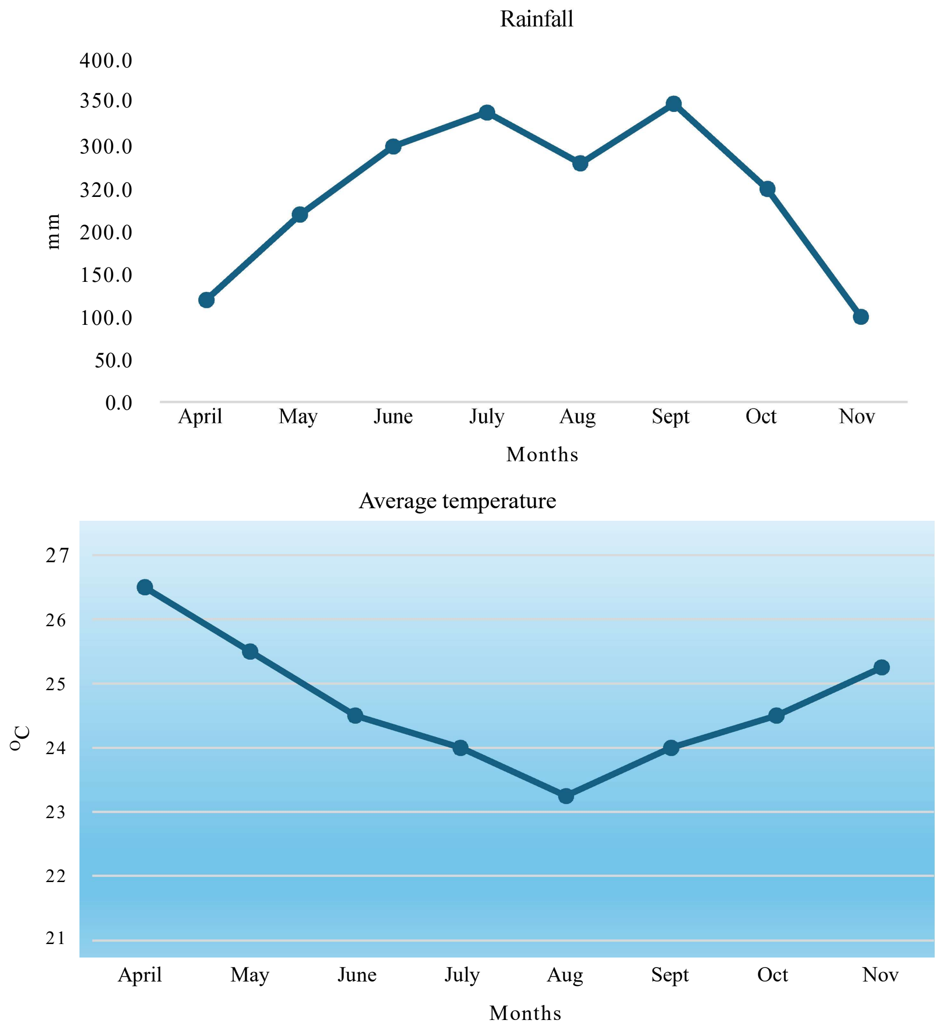

Figure 1. Rainfall and temperature during the period of experimentation.

analysed for their concentration of N, P and K (Tables 1 and 2). The laboratory analysis revealed that N averaged 2.7%, K averaged 2.1% and P averaged 0.4%. A composite soil sample made from 18 cores taken across the experimental plot prior to the commencement of the trial, was assessed for routine soil physical and chemical properties.

At harvest, for each treatment plot, soil was sampled at three points along the central row; bulked and a composite sample taken for routine physical and chemical properties for each cropping season. Methods for the routine determination of the soil physical and chemical properties are presented in Ewansiha *et al.* (2023).

FAW damage assessment. The severity of damage on maize plants by FAW, was determined at 4, 6, 8 and 10 WAS, using the 0–9 scale (Williams *et al.* 1989) as follows:

0 = no visible leaf damage;
1 = pinhole lesions on whorl leaves only;
2 = pinhole and shot-hole lesions on whorl leaves;

TABLE 1. Mineral composition of neem leaves harvested at each time of application

Nutrient (%)	First application	Second application	Third application	Average
N	2.8	2.76	2.4	2.7
P	0.36	0.34	0.37	0.4
K	2.11	2.08	2	2.1

TABLE 2. Methods used for the leaf analysis

Property	Method	References
Total N	Determination of Total N in plant materials (Micro-Kjeldhal Method)	1. Methods of Soil Analysis, Agron. Monograph No. 9, Part 2, pp.1149-1178, 1196. 1965 2. Aminco Reprint No. 104:1-4.1959 3. Jackson, Soil Chemistry, pp. 186. 1958. 4. A.O.A.C. Methods of Analysis, pp. 12.1955
P, K	Determinations of Ca, Mg, K and P in plant tissue (Dry Ashing)	Methods of Analysis, 11th Edition, A.O.A.C.

3 = a few small (5–10 mm) elongated lesions on leaves;
4 = several leaves with medium-sized (10–30 mm) lesions;
5 = several leaves with large elongated lesions or small portions eaten away;
6 = several leaves with elongated lesions and large portions eaten away;
7 = many elongated lesions with large portions eaten from leaves;
8 = many elongated lesions and numerous large portions eaten from leaves; and
9 = many leaves completely destroyed.

Weed impact assessment. Weed density was assessed at 3 and 5 WAS. The assessment was carried out within a 1 m x 1 m quadrant, established centrally in each plot for the purpose. Total weed density (weed density at 3 WAS + at 5 WAS) was expressed as number of weed plants per m^2. On the same plots and for the same weeds counted for density measurement, total dry weight was determined after air-drying to a constant weight, weighed and expressed in g m^{-2}.

Maize yield components. At physiological maturity, ears on maize plants inside the 1 m x 1 m quadrant were harvested and recorded as number of ears per m^2. The ears were dehusked, air-dried, threshed and the grain weight used to calculate grain yield per hectare. Also, 1000-seed weight was determined by counting and weighing 1000 seeds for each net plot.

Data analysis. Data collected were analysed using SAS for Windows Release 9.4 (SAS Institute, 2022). The SAS procedure used for the ANOVA was mixed model. Replication was treated as a random effect and mulch rate as a fixed effect in determining expected mean square and appropriate F-tests in the ANOVA. Differences between two significant treatment means were compared with Students' t-test, based on the standard error of the difference (SED) at 5% level of probability.

Count data for severity of damage on maize plants by FAW were transformed because normality test (PROC UNIVARIATE with the NORMAL option) showed that $P < 0.05$ for both Shapiro-Wilk and Kolmogorov-Smirnov tests. However, data on weed density were not transformed because they passed the normality test ($P > 0.05$). Pearson's correlation coefficient was used to test for a correlation between grain yield and other variables.

RESULTS

Soil nutrient dynamics and mulch rate optimisation. The results indicate that Neem leaf mulch (NLM) application significantly influenced soil fertility parameters (N, P and K) in a rate-dependent manner (Table 3). Baseline status indicate that initial soil values were 6.03 g kg^{-1} for organic carbon (OC), 0.51 g kg^{-1} for total nitrogen (TN), 5.86 mg kg^{-1} for available phosphorus (P), and 0.17 mg kg^{-1} for exchangeable potassium (K). Neem mulch application increased soil organic carbon, nitrogen, and available phosphorus relative to the control, with percentage increases ranging from 27.10 to 103.53% for organic carbon, 10.53 to 33.33% for nitrogen, and 36.49 to 79.18% for phosphorus. The magnitude of increase generally rose with mulch rate, with the 5 kg treatment producing the highest improvements across parameters. In contrast, potassium showed minimal and inconsistent changes, indicating a limited response to neem mulch application.

The C:N ratio increased progressively with neem mulch rate, from about 11.8 in the initial soil, to about 20.5 at the highest mulch rate (Table 4), indicating substantial carbon enrichment relative to nitrogen. The 0-3 kg treatments (≈13-16) fall within the optimal range for rapid mineralisation and synchronised nutrient release; while the 5 kg treatment (≈19-22) indicates carbon-rich conditions that may induce partial nitrogen immobilisation during decomposition.

Severity of FAW damage. Neem leaf mulch significantly ($P < 0.001$) reduced FAW damage severity across all observation periods (Table 5). Differences among treatments were not significant at 4 WAS, indicating limited early-stage effects. However, from 6 WAS onward, clear treatment effects emerged, with the un-mulched control recording significantly higher damage than all mulch treatments. At 8 and 10 WAS, FAW severity remained consistently highest in the control; while all neem mulch rates reduced damage to similarly low levels. The lack of significant differences among mulch rates at later stages, suggests that once a threshold mulch level is attained, additional biomass confers no further reduction in FAW damage.

Weed density and biomass. Increasing rates of NLM had a clear suppressive effect on weed population metrics (Table 6). NLM markedly reduced both total weed density and weed biomass compared with the control. Weed density declined from 223.62 plants m^{-2} in the un-mulched plots to 150.40, 117.29 and 53.50 plants m^{-2} at 1, 3 and 5 kg m^{-2} mulch rates, representing reductions of 32.74, 47.55 and 76.08%, respectively. Similarly, weed biomass decreased from 168.29 g m^{-2} in the control to 120.04, 99.00 and 42.18 g m^{-2}, corresponding to 28.67, 41.18 and 74.94% reductions at the corresponding mulch rates. These results indicate a strong, rate-dependent suppression of weeds by neem leaf residues.

Maize yield and components. Neem mulch significantly influenced all measured yield components (Table 7). The number of ears per m^{-2} increased by 13.3%, compared to the un-mulched treatment at 1 kg m^{-2}, reaching a maximum of 20.5% rise at 3 kg m^{-2}; before declining slightly to 18.1% at 5 kg m^{-2}. Similarly, 1000-seed weight increased progressively with mulch rate ($P < 0.05$), from

TABLE 3. Soil physical and chemical properties of the experimental site before the trial and after maize cropping

Mulch rate	OC	N	P	K
	(g kg^{-1})		(mg kg^{-1})	
Initial	6.03	0.51	5.86	0.17
Early season at harvest				
0 kg	7.38	0.57	6.33	0.21
1 kg	9.38	0.63	8.64	0.23
3 kg	9.78	0.68	8.67	0.20
5 kg	13.6	0.72	11.2	0.22
Late season at harvest				
0 kg	7.37	0.51	5.86	0.16
1 kg	9.98	0.60	9.02	0.16
3 kg	10.4	0.67	9.74	0.17
5 kg	15.0	0.68	10.5	0.17

TABLE 4. Calculated C:N ratios

Mulch rate	Mean OC (g kg^{-1})	Mean N (g kg^{-1})	C:N ratio
0 kg	7.38	0.54	13.67 : 1
1 kg	9.68	0.62	15.74 : 1
3 kg	10.09	0.68	14.96 : 1
5 kg	14.30	0.70	20.43 : 1

Note: Values are average of early and late season data

TABLE 5. Severity of plant damage in maize mulched with *Azadirachta indica A Juss* leaf residues

Mulch rate	4 WAS	6 WAS	8 WAS	10 WAS
0 kg m^{-2}	2.09	2.50	2.60	2.50
1 kg m^{-2}	1.97	2.09	1.58	1.32
3 kg m^{-2}	1.77	1.70	1.62	1.32
5 kg m^{-2}	1.94	1.70	1.58	1.32
Mean	1.94	2.00	1.85	1.62
SED	ns	0.2	0.15	0.12

Data were subjected to square root transformation (dx + 0.5) prior to analysis. Means presented are transformed values; separation based on SED at P = 0.05.; ns, not significant; SED, Standard Error of the Difference; ns, not significant

TABLE 6. Total weed density and total weed biomass in maize fertilised with *Azadirachta indica A Juss* leaf residues

Mulch rate	Total weed density (no. m^{-2})	Total weed biomass (g m^{-2})
0 kg m^{-2}	223.62	168.29
1 kg m^{-2}	150.40	120.04
3 kg m^{-2}	117.29	99.00
5 kg m^{-2}	53.50	42.18
Mean	136.20	107.38
SED	24.3591	14.7607

SED, standard error of the difference

TABLE 7. Number of ears, 1000-seed weight and grain yield of maize fertilised with *Azadirachta indica A Juss* leaf residues

Mulch rate	Number of ears (m^{-2})	1000-seed weight (g)	Grain yield (kg ha^{-1})
0 kg m^{-2}	4.43	196.25	1170.28
1 kg m^{-2}	5.01	215.00	2225.83
3 kg m^{-2}	5.33	242.50	3373.33
5 kg m^{-2}	5.23	254.50	4128.33
Mean	5.00	227.06	2724.44
SED	0.2097	13.1379	224.25

SED, standard error of the difference

196.3 g in the control to 215 g at 1 kg m^{-2}, 242.5 g at 3 kg m^{-2} and 254.5 g at 5 kg m^{-2}. Grain yield responded most strongly to NLM application ($P < 0.0001$), increasing from 1,170.3 kg ha^{-1} in the un-mulched plots, to 2,225.8 kg ha^{-1} at 1 kg m^{-2} (90.2% rise), 3373.3 kg ha^{-1} at 3 kg m^{-2} (188.2% rise), and 4128.3 kg ha^{-1} at 5 kg m^{-2} (252.8% rise).

Correlations between parameters. Correlation between plant FAW damage severity and grain yield was strongly dependent on the developmental stage at which damage occurred (Table 8). Damage at 4 weeks after sowing (WAS) was not significantly correlated with grain yield ($r = -0.036$, $P = 0.8436$). In contrast, damage incurred at 6, 8 and 10 WAS exhibited strong negative correlations ($r = -0.674$, $P < 0.0001$; $r = -0.552$, $P = 0.0011$; $r = -0.661$, $P < 0.0001$, respectively). Weed density demonstrated strong negative association with grain yield ($r = -0.771$, $P < 0.0001$). Similarly, weed biomass had strong and negative correlation with grain yield ($r = -0.809$, $P < 0.0001$). The correlation between number of ears and grain yield ($r = 0.637$, $P < 0.0001$) and between 1000 seed weight and grain yield ($r = 0.591$, $P = 0.0004$) were also significant but only modest.

DISCUSSION

Soil nutrient dynamics and mulch rate optimisation. The observed improvements in soil organic carbon (OC), total nitrogen (N), available phosphorus (P), and exchangeable potassium (K) following neem leaf mulch application demonstrate a clear enhancement

TABLE 8. Relationships between studied attributes and grain yield

Attributes	Correlation coefficient	Significance (P)
Severity of plant damage (4 WAS)	-0.03631	0.8436
Severity of plant damage (6 WAS)	-0.67404	<.0001
Severity of plant damage (8 WAS)	-0.55183	0.0011
Severity of plant damage (10 WAS)	-0.66105	<.0001
Weed density	-0.77131	<.0001
Weed biomass	-0.80939	<.0001
Number of ears	0.63688	<.0001
1000-seed weight	0.59069	0.0004

WAS = weeks after sowing

of soil fertility mediated by organic residue inputs. The progressive increase in OC with increasing mulch rates, culminating in a 148.8% rise above the initial level, reflects substantial carbon inputs and subsequent stabilisation within soil organic matter pools. Such responses are consistent with established evidence that repeated or high-biomass organic amendments increase particulate and mineral-associated organic carbon fractions, thereby improving soil structural stability and biological functioning (Six *et al*., 2002; Lal, 2004; Brady and Weil, 2016). The strong dose–response relationship observed (5 kg > 3 kg > 1 kg > control) further suggests that carbon saturation thresholds were not reached under the applied rates, indicating additional sequestration potential under higher residue loading in similar agroecological contexts (Blanco-Canqui and Lal, 2008).

The significant enrichment of soil N (up to 41.2%) under neem mulch treatments (Table 3), reflects rapid N cycling mediated by microbial decomposition of relatively high-quality organic residues. The nitrogen concentration of neem leaves (2.7%) exceeds the commonly cited 2% threshold for high-quality residues; implying a narrow C:N ratio and, therefore, favourable mineralisation dynamics (Palm *et al*., 2001; Giller, 2001). This likely enhanced ammonification and subsequent nitrification; leading to increased plant-available N pools. However, the magnitude of N response also suggests that synchrony between N release and crop demand may not be fully optimised; a common limitation in sole organic systems where mineralisation is governed by environmental constraints and microbial immobilisation dynamics (Vanlauwe *et al*., 2010). The consistent ranking pattern (5 kg > 3 kg > 1 kg > control) reinforces the role of residue quantity in regulating N supply capacity in tropical soils.

In contrast, the marked increase in available P despite the low intrinsic P content of neem residues (Table 3), highlights the dominance of indirect biogeochemical mechanisms over direct nutrient addition. Organic amendments are known to enhance P availability through multiple pathways, including organic acid production, competitive ligand exchange, and microbial stimulation, all of which reduce P sorption to Fe and Al oxides in highly weathered tropical soils (Hinsinger, 2001; Richardson *et al*., 2009). The near-equivalence of the 1 and 3 kg treatments, suggests a potential non-linear response, possibly driven by saturation of microbial-mediated solubilisation processes or localised P immobilisation at intermediate residue levels. Such non-linearities are widely reported in P cycling studies involving organic inputs in tropical agroecosystems (Oberson *et al*., 1996; Stewart *et al*., 2005).

The response of exchangeable K^+ was comparatively unstable and non-linear, despite the relatively high K content (2.1%) in neem leaves. This behaviour is consistent with the high solubility and mobility of K^+ in soil systems, where it is weakly retained on exchange sites and, therefore, highly susceptible to leaching and crop uptake losses (Mengel and Kirkby, 2001; Marschner, 2012). The irregular ranking pattern (1 kg > 5 kg > 3 kg > control), suggests that K dynamics were influenced more by transient release and redistribution processes than by cumulative accumulation. Similar variability has been reported in studies where organic residues temporarily elevate soil exchangeable K^+, but fail to sustain long-term increases due to rapid depletion pathways (Wang *et al*., 2010; Havlin *et al*., 2014).

The computed C:N ratios across neem mulch treatments (Table 4) revealed a progressive, but controlled increase with increasing mulch application rates, rising from 13.67:1 in the control to 20.43:1 at the highest mulch rate. This trend reflects the substantial contribution of organic carbon from neem leaf residues relative to nitrogen inputs, consistent with established evidence that organic amendments typically elevate soil carbon pools more rapidly than nitrogen due to differential mineralisation rates (Six *et al*., 2002; Lal, 2004). Despite this increase, all treatments remained within or close to the optimal range for mineralisation (10–20:1), indicating that nitrogen availability was largely sustained and not significantly limited by microbial immobilisation, as widely reported in tropical soil systems (Tiessen *et al*., 1994; Havlin *et al*., 2014).

The slightly elevated C:N ratio observed at 5 kg mulch (Table 4), suggests a shift towards greater carbon accumulation, which aligns with the marked increase in soil organic carbon at this rate. However, the ratio did not exceed thresholds typically associated with delayed nitrogen release, implying efficient decomposition and nutrient turnover of neem residues. This agrees with findings that high-quality plant residues with moderate lignin and polyphenol contents can support synchronised nutrient release and crop uptake (Palm *et al*., 2001; Kögel-Knabner, 2002).

Importantly, the non-linear pattern observed, where the 3 kg treatment exhibited a slightly lower C:N ratio than the 1 kg treatment, suggests enhanced nitrogen mineralisation at intermediate mulch rates, likely driven by optimal microbial activity and residue-soil interactions. This supports the concept that balanced organic inputs can stimulate microbial efficiency and nutrient cycling (Recous *et al*., 1995; Vanlauwe *et al*., 1996). Beyond the study objectives, these findings indicate that neem mulch not only improves nutrient availability, but also contributes to carbon stabilisation without disrupting nitrogen dynamics, reinforcing its role in sustainable soil fertility management (Giller, 2001; Udvardi *et al*., 2021).

Overall, the findings are consistent with the broader body of literature on organic amendments, where the addition of plant residues leads to significant improvements in soil OC and N, moderate to strong increases in P availability, and comparatively variable responses in K^+. The superior performance of the 5 kg mulch rate across most parameters (Table 7) highlights the importance of sufficient biomass input in maximising soil fertility benefits. These results reinforce the role of neem leaf mulch as a valuable component of integrated soil fertility management, particularly in low-input agricultural systems where sustainable nutrient supply is essential (Vanlauwe *et al*., 2015).

Fall armyworm damage. The delayed efficacy at 4 WAS may be attributed to the time required for the decomposition of fresh neem tissues and the subsequent systemic uptake of bioactive limonoids, such as azadirachtin, by the maize root system. Furthermore, the accumulation of these metabolites in the whorl, the primary feeding site for *S. frugiperda*, likely reaches an effective threshold only after repeated applications or sustained mineralisation of the mulch (Isman, 2006). From 6 WAS onwards, the strong reduction in damage severity in neem-mulched plots (Table 5), suggests effective suppression of the FAW feeding and development.

The pronounced reduction in damage at 8 and 10 WAS coincides with peak feeding activity by older larval instars, which are responsible for most economic damage in maize (Sparks, 1979; Cruz and Turpin, 1983). In addition to direct antifeedant and growth-regulating effects (Ewansiha, 2023), NLM may improve soil moisture retention and plant vigour, thereby enhancing maize tolerance to defoliation and reducing visible damage symptoms (Palm *et al*., 2001). The diminishing differences among NLM rates at later growth stages, suggest that once sufficient bioactive compounds accumulate, even lower application rates can provide effective protection. This finding is particularly relevant for resource-limited farming systems, where moderate NLM rates may offer a cost-effective and environmentally friendly alternative to synthetic insecticides. Integrating NLM with appropriate planting dates and regular field monitoring could, therefore, play a key role in sustainable, integrated pest management strategies for maize.

Weed density and biomass. The reduction in weed emergence is attributed to both physical and biochemical effects of mulch application on weed suppression. Organic mulches suppress weeds by reducing light penetration, moderating soil temperature, and creating a physical barrier that restricts seed germination and seedling emergence (Teasdale and Mohler, 2000; Litterick *et al*., 2004; Singh and Chamroy, 2025). These mechanisms likely contributed to the substantial decline in weed density observed. In addition, neem leaves contain allelochemicals such as azadirachtin and other bioactive compounds capable of inhibiting seed germination and early seedling growth (Isman, 2006; Koul, 2012). The stronger suppression observed at higher mulch rates (Table 6), suggests increased release and persistence of these compounds, enhancing weed control effectiveness.

The consistent reduction in weed biomass (Table 6) further indicates that neem mulch, not only limits weed emergence, but also suppresses subsequent growth and competitive ability, aligning with earlier reports on allelopathic weed suppression by organic residues (Weston, 1996). Overall, NLM achieved up to 75-76% reduction in weed density and biomass, demonstrating its effectiveness as a sustainable weed management strategy in maize production systems.

Yield and yield components. Neem leaf mulch significantly improved maize yield components (Table 6), reflecting enhanced soil-plant interactions driven by residue-mediated improvements in soil quality and nutrient cycling (Palm *et al*., 2001; Erenstein, 2003). These responses are strongly governed by residue carbon–nitrogen (C:N) dynamics, which regulate decomposition rates and N availability in soil systems (Swift *et al*., 1979; Myers *et al.*, 1994). The observed increase in C:N ratio from 11.82 (initial soil) to >20 at higher mulch rates, indicates progressive carbon enrichment and a shift in decomposition pathways, with implications for N mineralisation–immobilisation balance.

Moderate C:N conditions (≈13-16) at 1-3 kg m^{-2} likely enhanced synchronised nutrient release through rapid mineralisation, thereby improving maize growth, ear formation and grain yield (Palm *et al*., 2001; Agegnehu *et al*., 2016). This synchrony between nutrient supply and crop demand is consistent with established evidence that balanced organic residue inputs enhance yield components such as ear number and grain weight through improved nutrient-use efficiency (Chivenge *et al*., 2011). The increased ear number at 3 kg m^{-2} further reflects improved vegetative vigour associated with better soil moisture retention and moderated soil temperature under mulch cover, both of which are critical for reproductive development in maize (Erenstein, 2003).

At the highest application rate (5 kg m^{-2}), elevated C:N ratios (≈19-22) indicate a shift towards transient N immobilisation during early decomposition, a well-documented response to high-carbon organic inputs (Recous *et al.*, 1995; Mary *et al.*, 1996). Despite this, grain yield peaked at this rate, suggesting that any temporary N limitation was offset by improved soil physical conditions and sustained nutrient release during later decomposition stages. Such slow-release nutrient dynamics are characteristic of high-residue systems, where mineralisation continues throughout the crop growth cycle, particularly during grain filling (Trinsoutrot *et al.*, 2000). Consequently, grain yield increased substantially from ~1.1 t ha^{-1} in the control, to >4.1 t ha^{-1} under the highest mulch rate, underscoring the cumulative agronomic benefits of NLM.

Overall, NLM functions as a multifunctional soil amendment that regulates nutrient cycling through C:N-mediated processes; while simultaneously improving soil moisture conservation and microclimatic stability, thereby enhancing maize productivity under field conditions (Palm *et al.*, 2001; Erenstein, 2003).

Correlations between parameters. The correlation analysis clearly indicates that the impact of FAW damage on maize grain yield is highly stage-dependent, with early damage having negligible consequences and later damage exerting substantial yield penalties (Table 8). The absence of a significant relationship at 4 WAS (r = -0.036, P = 0.8436), suggests that maize plants possess a strong capacity for early vegetative compensation, likely through recovery mechanisms such as leaf regrowth and redistribution of assimilates. This conforms to previous reports that early defoliation in maize often results in minimal yield loss due to the crop's inherent resilience at the vegetative stage (Hruska and Gould, 1997; Cruz and Turpin, 1983).

In contrast, the strong negative correlations observed at 6, 8 and 10 WAS (r = -0.674, -0.552 and -0.661, respectively) indicate that damage during mid to late vegetative and early reproductive stages critically reduces grain yield (Table 8). These stages coincide with key physiological processes such as rapid biomass accumulation, ear initiation, and kernel set, during which stress directly limits sink formation and assimilate partitioning. Consequently, FAW infestation during these periods has a more pronounced effect on yield, as also reported in studies highlighting increased vulnerability of maize during reproductive transition phases (Day *et al.*, 2017; Prasanna *et al.*, 2018).

Clearly, the study confirms that weeds are a primary constraint on productivity (Table 8). Notably, weed biomass was a stronger predictor of yield loss than weed density. This aligns with the ecological principle that the total volume of competing vegetative material more accurately reflects the capture of light, water, and nutrients away from the crop than a simple count of individual weeds (Liebman and Dyck, 1993). The positive correlations with the number of ears and 1000-seed weight identify these variables as the specific mediators of yield loss. Under the pressure of weed competition and armyworm damage, the plant likely suffers from a reduction in both "sink number" (ears) and "grain filling" (seed weight). Ultimately, these relationships underscore that management strategies; such as NLM application or weed control, must be sustained well beyond the initial establishment phase to protect reproductive development and maximise yield.

Collectively, this study shows that applying NLM at rates equivalent to 30 and 50 t ha^{-1} is agronomically effective, but raises clear logistical constraints that must be acknowledged for real-world adoption. First, neem biomass availability is a primary limitation. Sourcing such large quantities of neem leaves would require either extensive plantation-scale production of *Azadirachta indica,* or coordinated collection from multiple locations, which may not be feasible for smallholder farmers. Seasonal leaf fall patterns further constrain supply consistency, potentially limiting timely application relative to planting windows.

Labour and handling requirements also increase substantially with higher mulch rates. Transporting and even distribution of 30-50 t ha^{-1} of material is labour-intensive operations, often requiring mechansation that is rarely accessible in many smallholder systems. Even where labour is available, the opportunity cost may be prohibitive compared to lower mulch rates or alternative soil fertility practices; this requires proper investigation.

From a field operations perspective, thick mulch layers at these rates can interfere with seedling emergence, planting precision, and early crop establishment if not properly managed. However, these same high rates likely contributed to the strong weed suppression and FAW reduction observed in the study, suggesting a trade-off between efficacy and practicality.

Economically, the cost-benefit balance becomes critical. While yield gains at 50 t ha^{-1} may justify the input under controlled or research conditions, scaling this to farm level would require valuation of labour, transport, and biomass against incremental yield returns.

A more practical implication of these findings is that moderate rates (e.g. 10–30 t ha^{-1}) or integrated approaches - combining neem mulch with reduced inorganic inputs or other organic residues - may offer a more scalable pathway. Future research should, therefore, focus on optimising lower, economically viable mulch rates, developing neem-based cropping systems that permits growing crops in neem alleys, evaluating on-farm biomass supply chains, and exploring mechanised or community-based systems for mulch production and application.

CONCLUSION

This study set out to evaluate the integrative role of neem leaf mulch (NLM) in improving soil fertility, suppressing fall armyworm (FAW), and controlling weeds in maize production. The results clearly demonstrate that NLM achieved all three objectives simultaneously: it significantly enhanced soil organic carbon, nitrogen, and phosphorus; reduced FAW damage at critical growth stages; and suppressed weed density and biomass in a strong, rate-dependent manner. These combined effects translated into substantial yield gains, with maize productivity increasing by over 250% at the highest application rate. Thus, the study confirms that neem leaf mulch is an effective, multifunctional input capable of addressing key agronomic constraints in a single, integrated approach.

Beyond the primary objectives, the study revealed important additional insights. Notably, the 3 kg m^{-2} rate provided an optimal balance between nutrient improvement and agronomic efficiency, while potassium response remained inconsistent due to its high mobility. Furthermore, yield was more strongly associated with weed biomass and late-stage FAW damage than with early pest incidence, highlighting critical intervention windows for management. Overall, neem leaf mulch emerges as a practical, low-cost and sustainable strategy for maize production in Nigeria. Future research should focus on long-term soil health effects, economic analysis of mulch application rates, and scaling the technology across diverse agro-ecological zones to enhance adoption.

ACKNOWLEDGEMENT

This study was funded by Tertiary Education Trust Fund (TETFUND) (Years 2023-2024 Batch 19), under Tetfund-Institution Based Research (IBR), University of Benin, Nigeria.

REFERENCES

Agegnehu, G., Nelson, P.N. and Bird, M.I. 2016. The effects of biochar, compost and their mixture on soil properties and yield of maize grown on a Ferralsol, *Soil Research* 54(2):217-228. https://doi.org/10.1071/SR15093

Badu-Apraku, B. and Fakorede, M.A.B. 2017. Advances in genetic enhancement of early and extra-early maize for sub-Saharan Africa. In: *Maize Breeding and Genetics*. Springer, Cham, pp. 427-452.

Bender, R.R., Haegele, J.W., Ruffo, M.L. and Below, F.E. 2013. Nutrient uptake, partitioning, and remobilization in maize hybrids. *Agronomy Journal* 105(1):161-170. https://doi.org/10.2134/agronj2012.0352

Benjamin, J., Idowu, O., Babalola, O.K., Oziegbe, E.V., Oyedokun, D.O., Akinyemi, A.M. and Adebayo, A. 2024. Cereal production in Africa: The threat of pests and weeds. *Agriculture and Food Security* 13(1):18. https://doi.org/10.1186/s40066-024-00452-1

Blanco-Canqui, H. and Lal, R. 2008. Principles of soil conservation and management. Springer, Dordrecht, Netherlands. 617pp.

Brady, N.C. and Weil, R.R. 2016. The nature and properties of soils. 15th edn. Pearson, Boston, USA. 1104pp.

Chivenge, P., Vanlauwe, B. and Six, J. 2011. Does the combined application of organic and mineral nutrient sources influence maize productivity? *Plant and Soil* 342:1-12. https://doi.org/10.1007/s11104-010-0675-7

Climate-Data.org 2016. Climate: Benin City. Available at: http://en.climatedata.org/location/764230/ (accessed 2026 December 16)

Cruz, I. and Turpin, F.T. 1983. Yield impact of larval infestations of *Spodoptera frugiperda* on maize. *Crop Science* 23:695-699.

Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., Colmenarez, Y., Corniani, N., Early, R., Godwin, J., Gomez, J., Moreno, P.G., Murphy, S.T., Oppong-Mensah, B., Phiri, N., Pratt, C., Richards, G., Silvestri, S. and Witt, A. 2017. Fall armyworm: Impacts and implications for Africa. *Outlooks on Pest Management* 28: 196-201. https://doi.org/10.1564/v28_aug_02

Deewan, P., Mundra, S.L., Singh, D., Meena, M., Verma, R. and Sharma, N.K. 2017. Effect of weed and nutrient management on maize productivity. *Journal of Pharmacognosy and Phytochemistry* 6(1): 271-274.

Dereje, G., Balemi, T. and Ashagre, H. 2018. Effect of weed interference on maize grain yield. *Ethiopian Journal of Crop Science* 6(1):63-80.

Erenstein, O. 2003. Smallholder conservation farming in the tropics and subtropics, *Agriculture, Ecosystems and Environment*, 100(1-3):27-43. https://doi.org/10.1016/S0167-8809(03)00145-9

Ewansiha, S.U., Enogieru, L.H., Aigbe, U.D. and Kamara, A.Y. 2023. Managing fall armyworm using neem leaf residues on maize. *Biological Agriculture & Horticulture* 39(4):305-315. https://doi.org/10.1080/01448765.2023.2219984

Fathi, A. 2022. Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review. *Agrisost* 28:1-8. https://doi.org/10.5281/zenodo.7143588

Food and Agriculture Organization (2023). FAOSTAT statistical database. FAO, Rome, Italy. URL: https://www.fao.org/faostat/

Gajalakshmi, S. and Abbasi, S.A. 2004. Neem leaves as a source of fertilizer. *Bioresource Technology* 94(1):77-82. https://doi.org/10.1016/j.biortech.2003.10.014

Gharde, Y., Singh, P.K., Dubey, R.P. and Gupta, P.K. 2018. Assessment of yield losses due to weeds. *Crop Protection* 107:

12-18. https://doi.org/10.1016/j.cropro.2018.01.007

Giller, K.E. 2001. Nitrogen fixation in tropical cropping systems. 2nd edn. CABI, Wallingford. United Kingdom. 423 pp.

Havlin, J.L., Tisdale, S.L., Nelson, W.L. and Beaton, J.D. 2014. Soil fertility and fertilizers. 8th edn. Pearson, Harlow, United Kingdom. 516 pp.

Hinsinger, P. 2001. Bioavailability of soil inorganic phosphorus in the rhizosphere. *Plant and Soil* 237:173-195. https://doi.org/10.1023/A:1013351617532

Hruska, A.J. and Gould, F. 1997. Fall armyworm (Lepidoptera: Noctuidae) and maize: Yield loss relationships and pest management thresholds. *Journal of Economic Entomology* 90: 611-619. https://doi.org/10.1093/jee/90.2.611

International Institute of Tropical Agriculture 2022. Maize production in sub-Saharan Africa. Available at: https://www.iita.org/cropsnews/maize/ (accessed 2025 July 31)

Isman, M.B. 2006. Botanical insecticides, deterrents and repellents. *Annual Review of Entomology* 51:45-66. https://doi.org/10.1146/annurev.ento.51.110104.151146

Kelita, P., Yolice, T., Trust, K., Vernon, H.K., Philip, C.S. and Steven, R.B. 2020. Bioactivity of pesticidal plants on fall armyworm larvae. *Plants* 9(1):112. https://doi.org/10.3390/plants9010112

Khamare, Y. and Marble, S.C. 2023. Mulching as a weed management tool in container plant production-review. *Frontiers in Agronomy* 5:1235196. https://doi.org/10.3389/fagro.2023.1235196

Kögel-Knabner, I. 2002. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. *Soil biology and biochemistry* 34(2):139-162. 10.1016/S0038-0717(01)00158-4

Koul, O. 2012. Neem: A tree for solving global problems. Springer. Dordrecht, Netherlands. 256 pp.

Lal, R. 2004. Soil carbon sequestration and food security. *Science* 304(5677):1623-1627. https://doi.org/10.1126/science.1097396

Liebman, M. and Dyck, E. 1993. Crop rotation and weed management strategies. *Ecological Applications* 3(1):92-122. https://doi.org/10.2307/1941795

Litterick, A.M., Watson, C.A., Atkinson, D. and Urwin, P.E. 2004. Soil and crop management practices to control weeds. *Soil and Tillage Research* 78(2):169-182. https://doi.org/10.1016/j.still.2004.02.001

Matova, P.M., Kamutando, C.N., Magorokosho, C., Kutywayo, D., Gutsa, F. and Labuschagne, M. 2020. Fall armyworm invasion and control practices. *Crop Science* 60(6):2951-2970. https://doi.org/10.1002/csc2.20258

Marschner, P. 2012. Mineral nutrition of higher plants. 3rd edn. Academic Press. London, UK. 651pp.

Mary, B., Recous, S., Darwis, D. and Robin, D. 1996. Interactions between decomposition of plant residues and nitrogen cycling in soil, *Soil Biology and Biochemistry* 28(1):73-82.

Mengel, K. and Kirkby, E.A. 2001. Principles of plant nutrition. 5th edn. Springer. Dordrecht, Netherlands. 849pp.

Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. 1994. The synchronization of nutrient mineralization and plant nutrient demand *Geoderma* 60(1-4):233-254.

Montezano, D.G., Sosa-Gómez, D.R., Specht, A., Roque-Specht, V.F., Sousa-Silva, J.C., Paula-Moraes, S.D., Peterson, J.A. and Hunt, T.E. 2018. Host plants of *Spodoptera frugiperda*. *African Entomology* 26:286-300. https://doi.org/10.4001/003.026.0286

Nigeria Seed Portal Initiative. 2026. SAMMAZ 52 maize variety. https://www.seedportal.org.ng/variety.php?keyword=Sammaz%2052&category=variety&varid= 283&cropid =7&task=view (Accessed: 18 April 2026).

Oberson, A., Friesen, D.K., Tiessen, H., Morel, C. and Stahel, W. 1996. Phosphorus dynamics in soils amended with organic residues in the tropics. *Soil Science Society of America Journal* 60(5):1583-1590. https://doi.org/10.2136/sssaj1996.03615995006000050038x

Ogeh, J. S. and Ukodo, E. 2012. Profile distribution of physical and chemical properties in soils of a toposequence in Benin, rainforest of Nigeria. *Nigerian Journal of Basic and Applied Sciences* 20(1):68-72.

Otim, M.H., Tay, W.T., Walsh, T.K., Kanyesigye, D., Adumo, S., Abongosi, J. and Okello, D. 2020. Insecticide resistance in fall armyworm. *Pest Management Science*, 76(3):865-878. https://doi.org/10.1002/ps.5683

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. 2001. Organic inputs for soil fertility management. *Agriculture, Ecosystems & Environment*, 83:27-42. https://doi.org/10.1016/S0167-8809(00)00210-3

Parven, A., Meftaul, I.M., Venkateswarlu, K. and Megharaj, M.. 2025. Herbicides in modern agriculture. *International Journal of Environmental Science and Technology* 22:1181-1202. https://doi.org/10.1007/s13762-024-05818-y

Pearsall, L.A. and Hogue, E.J. 2000. Use of azadirachtin as a larvicide or feeding deterrent for control of western flower thrips in orchard systems. *Phytoparasitica* 28(3):219-228. https://doi.org/10.1007/BF02981800

Prasanna, B.M., Huesing, J.E., Eddy, R. and Peschke, V.M. (Eds.) 2018. Fall armyworm in Africa: A guide for integrated pest management. Mexico: CIMMYT. 109pp.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S.K. and Chauhan, B.S. 2017. Weeds in a changing climate. *Frontiers in Plant Science* 8:108. https://doi.org/10.3389/fpls.2017.00108

Recous, S., Robin, D., Darwis, D. and Mary, B. 1995. Soil inorganic N availability: effect on maize residue decomposition. *Soil Biology and Biochemistry* 27(12):1529-1538. 10.1016/0038-0717(95)00096-W

Richardson, A.E., Barea, J.M., McNeill, A.M. and Prigent-Combaret, C. 2009. Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant and Soil* 321: 305-339. https://doi.org/10.1007/s11104-008-9815-9

SAS Institute. 2022. The SAS system for Windows (Release 9.4) [Computer software]. Cary, NC: SAS Institute.

Singh, M., Kukal, M.S., Irmak, S. and Jhala, A.J. 2021. Water use characteristics of weeds: A global review, best practices, and future directions. *Frontiers in Plant Science* 12:794090. https://doi.org/10.3389/fpls.2021.794090

Singh, D. and Chamroy, T. 2025. Impact of organic mulching on weed suppression, soil moisture conservation and yield in vegetable crops: A comprehensive review. *Journal of Advances in Biology & Biotechnology* 28(4):681-697. doi: 10.9734/jabb/2025/v28i42227

Six, J., Conant, R.T., Paul, E.A. and Paustian, K. 2002. Stabilization of soil organic matter. *Plant and Soil* 241:155-176. https://doi.org/10.1023/A:1016125726789

Sparks, A.N. 1979. Biology of fall armyworm. *Florida Entomologist* 62:82-87.

Stewart, W.M., Dibb, D.W., Johnston, A.E. and Smyth, T.J. 2005. The contribution of commercial fertilizer nutrients to food production. *Agronomy Journal* 97(1):1-6. https://doi.org/10.2134/agronj2005.0001

Swift, M.J., Heal, O.W. and Anderson, J.M. 1979. Decomposition in Terrestrial Ecosystems. Blackwell Scientific Publications. Oxford, UK. 371pp.

Teasdale, J.R. and Mohler, C.L. 2000. Weed emergence and mulch properties. *Weed Science* 48(3):385-392. https://doi.org/10.1614/0043-1745(2000)048[0385:TQRBWE]2.0.CO;2

Tiessen, H., Cuevas, E. and Chacon, P. 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371(6500):783-785. s://doi.org/10.1038/371783a0

Travlos, I., de Prado, R., Chachalis, D. and Bilalis, D.J. 2020. Herbicide resistance in weeds. *Frontiers in Ecology and Evolution* 8:213. https://doi.org/10.3389/fevo.2020.00213

Trinsoutrot, I., Recous, S., Bentz, B., Linères, M., Chèneby, D. and Nicolardot, B. 2000. Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under non-limiting nitrogen conditions. *Soil Biology and Biochemistry* 32(12-13): 2085-2098.

Udvardi, M., Below, F.E., Castellano, M.J., Eagle, A.J., Giller, K.E., Ladha, J.K., Liu, X., Maaz, T.M., Nova-Franco, B., Raghuram, N., Robertson, G.P., Roy, S., Saha, M., Schmidt, S., Tegeder, M., York, L.M. and Peters, J.W. 2021. A research road map for responsible use of agricultural nitrogen. *Frontiers in Sustainable Food Systems* 5: 660155. https://doi.org/10.3389/fsufs.2021.660155

Umweni, A.S., Uwadiae, I. and Okunsebor, F.E. 2014. Evaluating the distribution of some selected heavy metals in the soils of a university community farmland in Mid-Western Nigeria. *Journal of Research in Environmental and Earth Sciences* 1(3): 1-16.

Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. 1996. Residue quality and soil organic matter dynamics. *Soil Biology and Biochemistry* 28(8):1041-1049. https://doi.org/10.1016/0038-0717(96)00046-0

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E., Woomer, P.L. and Sanginga, N. 2010. Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39(1):17-24. https://doi.org/10.5367/000000010791169998

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M. and Van Asten, P. 2015. Sustainable intensification and the African smallholder farmer. *Current Opinion in Environmental Sustainability* 8: 15-22. https://doi.org/10.1016/j.cosust.2014.10.015

Wang, Y.P., Law, R. M. and Pak, B. 2010. A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere. *Biogeosciences* 7(7):2261-2282. https://doi.org/10.5194/bg-7-2261-2010

Weston, L.A. 1996. Allelopathy for weed management. *Agronomy Journal* 88(6): 860–866. https://doi.org/10.2134/agronj1996.00021962008800060008x

Williams, W.P., Buckley, P.M. and Davis, F.M. 1989. Combining Ability for Resistance in Corn to Fall Armyworm and Southwestern Corn Borer. *Crop Science* 29:913–915. https://doi.org/10.2135/cropsci1989.0011183X002900040014x

Xuan, T.D., Tsuzuki, E., Hiroyuki, T., Mitsuhiro, M., Khanh, T. D. and Chung, I.M. 2004. Evaluation on phytotoxicity of neem (Azadirachta indica. A. Juss) to crops and weeds. *Crop protection* 23(4):335-345. doi: 10.1016/j.cropro.2003.09.004

Yu, S.J. 1991. Insecticide resistance in fall armyworm. *Pesticide Biochemistry and Physiology* 39:84-91. https://doi.org/10.1016/0048-3575(91)90114-K

Zhang, L., C., Yan, W., Tan, G., Sun, N., Zhao, H., Li, F, Yu, J., Meng, X, and Bian, S. 2023. Effects of surface mulching on soil water temperature, physiological characteristics and yield of maize. *International Journal of Plant Production* 17(2):283-296. 10.1007/s42106-023-00238-3.

Zaller, J.G. 2020. Daily poison: Pesticides - an underestimated danger. Springer, Cham. Switzerland. 305pp.