Heliyon 10 (2024) e40973

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Influence of *Alectra vogelii* inoculation and phosphorus fertilizer application on phenology, yield components and grain yield of bambara groundnut genotypes

Rudo Musango[a,*], Tamado Tana[b,c], Stanford Mabasa[d], Edmore Gasura[d], Josephine Tafadzwa Pasipanodya[d], Ronald Mandumbu[e], Tonny Phirilani Tauro[f]

[a] *African Center of Excellence for Climate-Smart Agriculture and Biodiversity Conservation, Haramaya University, Ethiopia, P.O. Box 138, Dire Dawa, Ethiopia*
[b] *School of Plant Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia*
[c] *Department of Crop Production, Faculty of Agriculture, University of Eswatini, P.O. Luyengo, M 205, Ethiopia*
[d] *Department of Plant Production Sciences and Technologies, University of Zimbabwe, P.O. Box 167, Mt Pleasant, Harare, Zimbabwe*
[e] *Department of Crop Science, Faculty of Agriculture and Environmental Science Bindura University of Science Education, P. Bag 1020, Bindura, Zimbabwe*
[f] *Department of Soil Science and Productivity, Marondera University of Agricultural Sciences and Technology, P.O Box 35 Marondera, Zimbabwe*

ARTICLE INFO

Keywords:
Parasitic weed
Resistant
Stimulation
Tolerant
Yellow witchweed

ABSTRACT

In sub-Saharan Africa, the parasitic *Alectra vogelii* is seriously threatening Bambara groundnuts, farmers to suffer yield losses of up to 100 %. The objective of this study was to determine the effects of phosphorus (P) application and *Alectra vogelii* inoculation on Bambara groundnut genotypes for growth and reproductive phrase. The experiment was conducted in 2020 at the Henderson Research Station in Mazowe, Zimbabwe in a 2 × 2 × 26 factorial design with 26 genotypes arranged in a completely randomized design (CRD) with four replications, two P rates (0 and 20 kg ha-^{1}) and two levels of inoculation (with and without *Alectra vogelii*). Half of the perforated black plastic bags were inoculated with *Alectra vogelii* seeds. The results showed a significant ($p < 0.001$) interaction between P application and *Alectra vogelii* inoculation, leading to decreased *Alectra vogelii* counts after 109 days, days to maturity, days to flowering, and chlorophyll content. There was a significant ($p < 0.001$) interaction between Bambara groundnut genotypes and *Alectra*-inoculation on number of pods, pod weight, number of seeds, and grain yield. *Alectra vogelii* parasitism significantly ($p < 0.001$) decreased number of pods, pod weight, number of seeds, and grain yield across all groundnut genotypes. G2, G23, G24, and G25 genotypes exhibited tolerance to *Alectra vogelii*, with grain yield per plant of 4.82, 6.12, 5.65, and 5.34 g, respectively, outperforming other genotypes. It was found that the combination of 20 kg P ha^{-1} with *Alectra*-resistant genotypes improved Bambara groundnut productivity.

1. Introduction

According to HLPE [1], projected human population, threats of pandemics like COVID-19, climate change, and conflicts are

---

* Corresponding author.
E-mail address: musangor@yahoo.co.uk (R. Musango).

https://doi.org/10.1016/j.heliyon.2024.e40973
Received 5 May 2024; Received in revised form 2 December 2024; Accepted 4 December 2024

increasing globally, as well as nutritional insecurity. In southern Africa, maize is this staple crop that predominantly provides starch and relatively low protein which negatively affects human health and nutritional security [2,3]. As a result, there is a critical need to improve nutrition and food security in Africa.

According to Dikr and Abayechaw [4], legumes increase cereal crop productivity, through improved soil fertility, thus boosting nutritional security. Climate change-induced heat and drought have led to decreased yields in legumes such Faba beans, soybeans, and common beans, as well as cereals like rice, maize, and wheat [5,6]. Bambara groundnut is a legume that is underutilised compared to cash crops. This crop is typically associated with subsistence agriculture, with women having important roles in production and processing [7].

In most parts of Zimbabwe, farmers rely on retained seed from local landraces or purchased from the markets [8]. This has resulted in low germination rates and lower yields in some districts [9]. In Zimbabwe, two Bambara groundnut varieties called "Mana and Kazuma" were registered as commercial in 2004 [10], but are not available on the markets. The varieties are conserved as germplasm at Crop Breeding Institute (CBI) in Zimbabwe [10]. Bambara groundnut grain provides about 15%–25 % protein, 49%–63.5 % carbohydrate, 4.5–7.4 % fat, 5.2%–6.4 % fiber, and 2 % minerals [11].

In extensively practiced subsistence farming, biotic stressors caused by parasitic weeds (*Alectra vogelii* and *Striga*) hinder the production of Bambara. Abiotic stresses, such as poor soil fertility, low organic matter content, and limited plant available P and micronutrients, can also constrain Bambara production [12,13]. In Zimbabwe, farmers have continued to use local landraces, usually those that are tolerant to *Alectra vogelii* through selection.

The life cycle of the autogamous parasite *Alectra vogelii* is similar to that of *Striga* species because their control and management are the same. According to Fernández-Aparicio et al. [14], several East, Central, and Southern African nations are facing serious threats from *Alectra vogelii*. The adaptation or dormancy mechanisms that allow seeds to remain alive in the soil for several years make it challenging to control *Alectra vogelii* [15,16]. *Alectra vogelii* has evolved to produce numerous tiny seeds with extended viability and specific germination requirements as an adaptation to its parasitic lifestyle [17]. *Alectra vogelii* seeds can only germinate after being influenced by external germination stimulants [17]. Typically, strigolactones are exuded by root host and non-host plant species used as trap crops such as sunflower, cotton, sunhemp, and lablab [18,19]. Strigolactones are hormones produced by plants that regulate the shoot and root architecture [20]. Additionally, strigolactones act as signals for host recognition by arbuscular mycorrhizal fungi [17, 20] and Rhizobia while also triggering the germination of parasitic weed seeds like those of *Alectra* spp.

Acidic soils favor *Alectra vogelii* because they provide a favorable environment for the increased stability of strigolactones, which promote the germination of parasitic weeds [Mandumbu et al. [21]. *Alectra vogelii* is a troublesome parasitic weed that reduces the yield of various crops, including cowpeas and groundnuts, by 50–100 %, depending on the severity of infestation in most parts of Africa [21–24]. Managing this critical threat to Bambara production is therefore imperative.

Interventions recommended to mitigate yield losses from *Alectra vogelii*, as proposed by Mutsvanga et al. [25], include applying organic materials and nitrogen fertilizers. Theories suggest that fertilizers can suppress parasitic weed infestations by promoting plant health and resistance [26]. Improved nutrients promote plant health, while high nutrient levels, particularly nitrogen, decrease strigolactone release from host roots, reducing germination of *Alectra vogelii* and *Striga* spp. seeds and reducing infestation levels [25, 27,28]. Additionally, high soil organic matter encourages biological activity, potentially accelerating the decay or predation of weed seeds [29]. However, the lack of known Bambara genotypes that are resistant or tolerant to *Alectra vogelii* exacerbates this situation. Research on the responses of cowpea [30] and groundnut genotypes to *Alectra vogelii* in Zimbabwe [22] suggest that identifying and cultivating Bambara genotypes with potential resistance or tolerance to *Alectra vogelii* could be a solution. However, more documentation is needed on the effects of *Alectra* infection on Bambara genotypes in Zimbabwe. Nutritional management [28] and varietal control have been used to control parasitic weeds; however, knowledge regarding P management in Bambara cropping systems still needs to be improved. Therefore, the objective of this study was to determine the effects of P application and *Alectra vogelii* inoculation on Bambara groundnut genotypes for growth and reproductive phrase.

Table 1
Selected physical and chemical properties of the experimental soil collected from Henderson Research Station Farm.

Soil properties	Value
Soil pH (Ca-Cl$_2$)	4.10
Sand (%)	69.80
Silt (%)	8.50
Clay (%)	16.60
Textural class	Sandy loam
Total N (%)	0.10
Available P (mg kg^1)	3.00
Exchangeable Ca^{2+} (cmolc kg-^{1})	1.22
Exchangeable Mg^{2+} (cmolc kg-^{1})	0.41
Exchangeable K + (cmolc kg-^{1})	0.07

2. Materials and methods

2.1. Study site

The trial was conducted during the 2020 cropping season at an open space at Henderson Research Station (17° 34′ South, 30° 58’ East and an altitude of 11205 m (above sea level). The site is in Mazowe, 25 km from Harare. The soil used in the experiment was sandy loamy in texture, with medium plant availability (P), low nitrogen, and exchangeable potassium (K), but had a good calcium (Ca) to magnesium (Mg) ratio for any crop production (Table 1).

2.2. Experimental design and seeds source

A 2 x 2 x 26 factorial arrangement trial was set up in a completely randomized design with four replications, two levels of inoculation (with and without *Alectra vogelii*), two P rates (0 and 20 kg ha^{-1}), and 26 genotypes. The experiment involved screening of 25 Bambara groundnut local landraces and one Mana variety (standard check). Nine landraces and one Mana variety were obtained from the Crop Breeding Institute (CBI) and nine from the Plant Genetic Resources and Biotechnology Institute (PGRBI) of both Agricultural Research Innovation and Department of Directorate, Harare Research Station, in Zimbabwe. The other seven were collected from farmers in Buhera communal area (BCA), Manicaland Province of Zimbabwe. The *Alectra vogelii* seeds were sourced from farmers’ fields in the Rushinga communal area (RCA), Mount Darwin, Zimbabwe, for parasitic weed inoculation (Table 2).

2.3. Experimental procedure

Bambara seeds were planted in perforated black plastic bags (320 mm × 140 mm x 180 mm). These bags were filled with sandy loam soil sourced from the Henderson Research Station farm in Zimbabwe. For the fertilizer treatments, single superphosphate (SSP) (8.5 % P) was applied before planting to the perforated black plastic bags at application rates of 0 kg P ha^{-1} and 20 kg P $ha^{-1.}$ For the control group, no additional fertilizers were applied. The top 100 mm of soil was taken out of 416 perforated black plastic bags in order to create an *Alectra*- inoculated treatment. The 100 mm sub-sample collected from each perforated black plastic bags were placed into clean plastic bags, mixed with 0.02 g of *Alectra vogelii* seeds, and returned to the original perforated black plastic bags. The remaining 416 bags were without *Alectra vogelii* seeds and were used as the control. Pre-conditioning was performed to ensure that *Alectra vogelii* seeds germinated optimally by breaking dormancy [31]. Pre-conditioning occurs when *Alectra vogelii* seeds need moisture for two weeks before they respond to germination stimulants from Bambara genotype roots. Two Bambara seeds were planted in each bag, watered soil moisture kept at field capacity until seedling emergence. Two weeks after emergence, Bambara groundnut seedlings were thinned to one per bag. The plants were watered when necessary. All other weeds expect *Alectra vogelii* were manually pulled out.

Table 2
Bambara groundnut genotypes and *Alectra vogelii* seeds used for the study.

Source	Genotype	Variety/Accession	Region of collection	Local name
CBI	**G1**	Cultivar CBI-1	Harare	Mana
	G2	LR2018-2-1	Manicaland Province	Landrace
	G3	LR2018-3-2	Manicaland Province	Landrace
	G4	LR2018-4-3	Manicaland Province	Landrace
	G5	LR2018-5-4	Manicaland Province	Landrace
	G6	LR2018-6-5	Manicaland Province	Landrace
	G7	LR2018-7-7	Manicaland Province	Landrace
	G8	LR2018-8-11	Manicaland Province	Landrace
PGRBI	**G9**	KMMC086	Harare	Deep red
	G10	KMMC107	Harare	Cream
	G11	KMMC219	Harare	Cream
	G12	KMMC378	Harare	Red
	G13	KMMC1191	Harare	Red
	G14	NPGRC6320	Harare	Black
	G15	NPGRC6314	Harare	Red flash
	G16	NPGRC6321	Harare	Red flash
	G17	NPGRC6317	Harare	Cream chipofu
	G18	NPGRC6315	Harare	V-black
	G19	NPGRC6325	Harare	V-red
BCA	**G20**	BH01	Manicaland Province	Landrace
	G21	BH02	Manicaland Province	Landrace
	G22	BH03	Manicaland Province	Landrace
	G23	BH04	Manicaland Province	Landrace
	G24	BH05	Manicaland Province	Landrace
	G25	BH06	Manicaland Province	Landrace
	G26	BH07	Manicaland Province	Landrace
RCA	**Yellow-witch weed**	*Alectra vogelii*	Mashonaland East Province	Parasite weed

2.4. Data collection and measurement of crop phenology, growth parameters, yield components and yield

The chlorophyll content was recorded from Bambara genotypes and *Alectra vogelii* shoot counts were recorded at 7–13 weeks after planting, *Alectra vogelii* counts were recorded 90 days after planting (AC90DAP) and at 109 days after planting (AC109DAP). Weekly measurements of chlorophyll were taken using a portable SPAD-502 (Minolta Corporation) from week eight to week thirteen after planting. Measuring chlorophyll content was important as it indicated the plant's health and photosynthetic efficiency, which can be affected by *Alectra vogelii* infestation. The number of days to flowering in Bambara groundnut were recorded from planting to the initial appearance of the first flower. Days to 90 % physiological maturity were recorded when the vine began to turn yellow and leaves were shed.

At the end of week 13, fresh Bambara plants were cut at the soil line and placed inside a khaki paper. Then roots were uprooted when the soil was still moist to ensure all root structures were collected, including those affected by *Alectra vogelii*, were carefully collected. The roots were cleaned under running water to obtain fresh root biomass. The fresh biomass was oven dried at 60 °C to determine dry weight. Yield and yield components consisted of the following; number of pods, number of seeds per pod, seed weight, and grain yield weight. Pod weight, seed weight and grain yields were measured using a sensitive balance (Compact Scale and Balance) and Bance-Adams Equipment. The grain yield per plant (GYP (g)) was calculated as follows:

GYP (g) = number of pods × number of seeds per pod × weight of one seed [32].

2.5. Data analysis

The data was subjected to analysis of variance (ANOVA) using R-Statistical Package version 4.3.2 to determine the effects of the treatments. Bartlett's test was used to check for the homogeneity of variance. Significantly, different treatment means were compared using the least significant difference (LSD) test at 5 % level of significance.

3. Results

3.1. Interaction effects on Alectra vogelii shoot count at 109 days after planting

P rate effects on *Alectra vogelii* counts at 109 days after planting were significant ($p < 0.05$) (Table 3). The interaction effects between P rate and *Alectra*-inoculation significantly ($p < 0.01$) influenced the *Alectra vogelii* shoot count at 109 days after planting (Table 3). *Alectra vogelii* shoots varied across all P rates, but *Alectra vogelii* shoot count was reduced at the application rate of 20 kg P ha^{-1} and this also reduced *Alectra vogelii* shoot count. Highest *Alectra vogelii* shoot counts (0.63) were observed from 0 kg P ha^{-1}, while the 20 kg P ha^{-1} had the lowest count of 0.17. *Alectra vogelii* shoot counts were significantly reduced by addition of 20 kg P ha^{-1} (Table 3).

3.2. Interaction effects on leaf chlorophyll content

Highly significant ($p < 0.001$) differences between P rates were recorded in chlorophyll content of plants. *Alectra*-inoculated had significant ($p < 0.05$) effects in chlorophyll content on Bambara groundnut genotypes. Variation attributable to the interaction between P rate and *Alectra*-inoculation was significant ($p < 0.01$) for chlorophyll content (Table 3). Bambara genotypes that received 20 kg P ha^{-1} fertilizer had significantly lower chlorophyll content compared to those that received 0 kg P ha$^{-1.}$ The chlorophyll content in the *Alectra*-inoculated Bambara genotypes increased when 20 kg P ha^{-1} was added compared to the control in genotypes that were not

Table 3
P rate and *Alectra vogelii* interaction and their effects on Bambara groundnut genotypes.

P rates (kg ha^{-1})	Treatments	*Alectra vogelii count*	Chlorophyll content	Days to flowering	Days to maturity
0	Non-inoculated	0.0^{b}	47.56^{a}	53.77^{b}	109.85^{a}
20	Non-inoculated	0.0^{b}	24.52^{c}	22.76^{c}	59.77^{c}
0	Inoculated	0.63^{a}	46.91^{b}	59.22^{a}	102.78^{b}
20	Inoculated	0.17^{b}	34.52^{b}	51.62^{b}	79.42^{b}
LSD (0.05)		0.21	5.29	5.36	10.96
p-value		0.01	0.01	0.001	0.001
P rate					
0		0.32^{a}	47.24^{a}	56.50^{a}	106.31^{a}
20		0.09^{b}	29.52^{b}	34.69^{b}	69.60^{b}
LSD (0.05)		0.15	3.74	3.79	7.75
p-value		0.05	0.001	0.001	0.001
Alectra vogelii					
	Inoculated	0.40^{a}	40.72^{a}	55.48^{a}	91.10^{a}
	Non-inoculated	0.0^{b}	36.04^{b}	35.76^{b}	84.81^{a}
LSD (0.05)		0.15	3.74	3.37	7.75
p-value		0.001	0.05	0.001	ns

Means followed by different superscripts are significantly different at $p < 0.05$.

inoculated (Table 3). Furthermore, the chlorophyll content under control on non-*Alectra* inoculated plants was significantly higher with 47.56 mmol compared to that at 20 kg P ha^{-1}, which recorded the least at 24.52 mmol in non-*Alectra* inoculated plants (Table 3). The application of P fertilizer significantly reduced the chlorophyll content of Bambara genotypes.

3.3. Days to flowering of Bambara

Alectra-inoculation and P rate significantly ($p < 0.001$) influenced days to flowering (Table 3). In addition, there were significant ($p < 0.001$) interaction effects ($p < 0.001$) of *Alectra*-inoculation and P application on days to flowering (Table 3). Bambara grown in *Alectra*-inoculated treatment flowered late at day 59 compared to those grown in non-*Alectra*-inoculated treatment, which started flowering at day 54 (i.e., 5 day difference). However, Bambara grown in *Alectra*-inoculated treatments and 20 kg P ha^{-1} started to flower at day 52, whereas in non-inoculated treatments, flowering commenced at day 25 (i.e., a significant difference of 17 days). In contrast, flowering of Bambara grown under the control in non-inoculated treatments (without P fertilizers) commenced on day 54, whereas at 20 kg P ha^{-1} in non-inoculated treatment, it significantly decreased the number of days to flowering (Table 3).

3.4. Days to maturity of bambara

P rate significantly ($p < 0.001$) influenced days to maturity. However, there were significant ($p < 0.001$) interaction effects of *Alectra*-inoculation and P application on the days to maturity of the Bambara genotypes (Table 3). Conversely, the application of 20 kg P ha^{-1} significantly reduced the maturity time regardless of *Alectra*-inoculation in the treatments. Under inoculated treatments, Bambara matured at approximately 79 days, whereas non-inoculated Bambara matured at approximately 60 days, with a difference of 19 days. (Table 3).

3.5. Number of pods of Bambara

Alectra-inoculation and P application had significant effects ($p < 0.001$) on the number of pods, while the *Alectra*-inoculation and Bambara genotypes interaction had significant effects ($p < 0.01$) on the number of pods (Table 4). The number of pods under *Alectra*-inoculation increased after the application of 20 kg P ha^{-1}. There was a significant ($p < 0.01$) interaction effect between Bambara genotype and *Alectra*-inoculation on the number of pods per plant (Table 4). The genotypes that performed well and attained the highest number of pods in the inoculated treatments were G23 (13 pods), G24 (15 pods), and G26 (9 pods) (Table 4).

Table 4
Effect of *Alectra vogelii*-inoculation on the number of pods per plant and the pod weight (g) of Bambara genotypes.

Bambara genotypes	Number of pods per plant		Pod weight	
	Inoculated	Non-inoculated (Control)	Inoculated	Non-inoculated (Control)
G1	3.38^{m}	4.25^{klm}	0.85^{n}	$2.28^{ghijklmn}$
G2	$8.88^{cdefghijklm}$	$11.75^{bcdefghij}$	$3.78^{cdefghijklmn}$	$4.98^{abcdefghijkl}$
G3	$8.13^{defghijklm}$	$7.63^{defghijklm}$	$2.73^{fghijklmn}$	$2.13^{hijklmn}$
G4	4.50^{klm}	$8.13^{defghijklm}$	1.09^{mn}	$3.04^{efghijklmn}$
G5	5.88^{ijklm}	$10.63^{bcdefghijkl}$	1.14^{lmn}	$5.45^{abcdefghi}$
G6	5.50^{ijklm}	5.63^{ijklm}	$1.85^{hijklmn}$	$2.17^{hijklmn}$
G7	$8.13^{defghijklm}$	$10.25^{bcdefghijklm}$	$2.04^{hijklmn}$	6.18^{abcdef}
G8	5.25^{ijklm}	$7.50^{fghijklm}$	1.08^{mn}	$2.61^{fghijklmn}$
G9	6.50^{hijklm}	13.88^{bcdef}	$2.22^{ghijklmn}$	$5.65^{abcdefgh}$
G10	$7.75^{defghijklm}$	23.00^{a}	$2.06^{hijklmn}$	8.00^{ab}
G11	5.00^{jklm}	4.50^{klm}	$2.48^{fghijklmn}$	1.67^{ijklmn}
G12	4.00^{klm}	$10.50^{bcdefghijkl}$	1.33^{klmn}	$5.29^{abcdefghij}$
G13	6.13^{ijklm}	$10.38^{bcdefghijkl}$	1.78^{ijklmn}	$2.68^{fghijklmn}$
G14	4.00^{klm}	14.50^{bcde}	1.20^{lmn}	8.07^{ab}
G15	3.88^{lm}	$9.75^{bcdefghijklm}$	0.99^{n}	8.41^{a}
G16	6.00^{ijklm}	13.50^{bcdefg}	$2.29^{ghijklmn}$	8.52^{a}
G17	$10.13^{bcdefghijklm}$	$12.00^{bcdefghi}$	$3.42^{defghijklmn}$	$4.90^{abcdefghijklm}$
G18	4.38^{klm}	15.63^{bc}	1.16^{lmn}	7.88^{ab}
G19	6.50^{hijklm}	$9.25^{cdefghijklm}$	1.78^{ijklmn}	7.11^{abcd}
G20	6.00^{ijklm}	$10.88^{bcdefghijk}$	1.59^{jklmn}	$4.32^{bcdefghijklmn}$
G21	4.63^{klm}	16.63^{ab}	1.47^{jklmn}	7.62^{abc}
G22	$6.88^{ghijklm}$	15.23^{bc}	$2.43^{fghijklmn}$	6.86^{abcde}
G23	$13.13^{bcdefgh}$	$7.00^{fghijklm}$	$6.05^{abcdefg}$	$3.27^{efghijklmn}$
G24	14.63^{bcd}	$11.63^{bcdefghij}$	6.71^{abcde}	$5.16^{abcdefghijk}$
G25	$10.00^{bcdefghijklm}$	$9.63^{cdefghijklm}$	$4.47^{bcdefghijklmn}$	$4.52^{bcdefghijklmn}$
G26	$9.25^{cdefghijklm}$	5.23^{ijklm}	$5.25^{abcdefghij}$	$1.85^{hijklmn}$
LSD 0.05)	6.990		3.840	
p-value	0.01		0.001	

Means followed by different superscripts are significantly different at $p < 0.05$.

3.6. *The pod weight of bambara*

Alectra-inoculation had a significant ($p < 0.001$) effect on pod weight per plant (Table 4). Also, P rate significantly ($p < 0.01$) influenced pod weight of Bambara genotypes (Table 4). Furthermore, Bambara genotypes had significant ($p < 0.05$) differences on pod weight (Table 4). There was a significant ($p < 0.001$) interaction effect between Bambara genotypes and *Alectra vogelii* for pod weight per plant (Table 4). In the non-inoculated treatments, most genotypes had pod weights with >4 g per plant, except for G1, G3, G4, G6, G8, G11, G13, G23 and G26 which had low pod weights (<4 g per plant) (Table 4). The genotypes that performed well in the inoculated treatments were G23 (6.05 g), G24 (6.71 g), and G26 (5.25 g), that had also high pod weight (Table 4).

3.7. *Number of seeds of Bambara*

P application and *Alectra*-inoculation had a significant ($p < 0.001$) effect on the number of seeds produced per plant. Bambara genotypes significantly ($p < 0.01$) differed in the number of seeds per plant (Table 5). The number of seeds per plant was significantly ($p < 0.01$) affected by the interaction between *Alectra vogelii* and Bambara genotypes (Table 5). Genotypes G11, G23, G24, and G25 had higher numbers of seeds per plant under *Alectra*-inoculation (Table 5). The other genotypes had fewer seeds (less than five seeds per plant), whereas most genotypes in the non-inoculated treatments had more seeds (>20 seeds per plant). The highest number of seeds was from the Bambara genotype G10 (21.88), whereas genotypes G10, G14, G16, G18 and G21 had more than >14 seeds per plant (Table 5).

3.7.1. *Grain yield of bambara*

The grain yield of Bambara groundnut was significantly ($p < 0.01$) affected by genotypes and P rates (Table 5). Moreover, the interaction effect of Bambara groundnut genotypes and *Alectra*-inoculation had significant ($p < 0.001$) influence on grain yield. Three Bambara groundnut genotypes G23, (6.21 g), G24 (5.65 g) and G25 (5.34 g) had the highest yield under inoculated treatment (Table 5). It was observed that the harmful effects *of Alectra vogelii* on grain yield of Bambara can be reduced by adding at least 20 kg P ha^{-1} (Table 5). Higher grain yields were obtained from G10, G16, and G22 (>8 g) in non-inoculation treatments.

Table 5
Effect of *Alectra vogelii*-inoculation on the number of seeds per plant and grain yield (g) Bambara genotypes.

Bambara genotypes	Number of seeds per plant		Grain yield per plant (g)	
	Inoculated	Non-inoculated (Control)	Inoculated	Non-inoculated (Control)
G1	3.13^{klm}	$5.38^{efghijklm}$	0.71^{m}	$1.72^{ghijklm}$
G2	$7.00^{defghijklm}$	$9.38^{bcdefghijkl}$	$4.82^{bcdefghijk}$	$4.63^{bcdefghijklm}$
G3	$6.00^{efghijklm}$	$5.63^{efghijklm}$	$3.10^{efghijklm}$	$2.29^{fghijklm}$
G4	2.75^{lm}	$7.00^{defghijklm}$	1.32^{ijklm}	$3.19^{efghijklm}$
G5	$5.62^{efghijklm}$	$9.63^{bcdefghijk}$	0.84^{lm}	$4.27^{cdefghijklm}$
G6	$4.5^{ghijklm}$	$5.13^{fghijklm}$	1.58^{hijklm}	$1.90^{ghijklm}$
G7	$6.88^{defghijklm}$	$9.50^{bcdefghijk}$	$2.16^{fghijklm}$	$4.56^{cdefghijklm}$
G8	3.25^{jklm}	$5.50^{efghijklm}$	1.03^{klm}	$2.24^{fghijklm}$
G9	$6.25^{defghijklm}$	11.00^{bcdefg}	$1.98^{ghijklm}$	6.43^{abcde}
G10	$6.38^{defghijklm}$	21.88^{a}	$1.70^{ghijklm}$	9.68^{a}
G11	$6.75^{defghijklm}$	3.25^{jklm}	1.27^{jklm}	1.54^{hijklm}
G12	$3.25j^{klm}$	$9.88^{bcdefghij}$	1.08^{klm}	$5.16^{bcdefghij}$
G13	$5.13^{fghijklm}$	$10.13^{bcdefghi}$	$1.69^{ghijklm}$	$2.26^{fghijklm}$
G14	$5.00^{fghijklm}$	14.75^{bc}	0.77^{lm}	6.37^{abcde}
G15	2.00^{m}	$9.38^{bcdefghijkl}$	1.07^{klm}	6.30^{abcde}
G16	$4.63^{ghijklm}$	15.38^{ab}	$2.17^{fghijklm}$	8.58^{ab}
G17	$7.75^{defghijklm}$	11.88^{bcde}	$3.36^{efghijklm}$	$4.03^{defghijklm}$
G18	3.50^{ijklm}	14.63^{bc}	1.02^{klm}	7.73^{abcd}
G19	4.00^{ijklm}	$8.63^{cdefghijklm}$	1.58^{hijklm}	$4.73^{bcdefghijkl}$
G20	$5.00^{fghijklm}$	$10.00^{bcdefghi}$	1.28^{jklm}	$3.61^{efghijklm}$
G21	4.13^{hijklm}	15.88^{ab}	1.23^{jklm}	8.00^{abc}
G22	$6.25^{defghijklm}$	11.50^{bcdef}	$2.47^{efghijklm}$	9.93^{a}
G23	11.63^{bcdef}	$6.00^{efghijklm}$	6.12^{abcdef}	$2.82^{efghijklm}$
G24	12.88^{bcd}	$10.75^{bcdefgh}$	5.65^{bcdefg}	$5.18^{bcdefghij}$
G25	$8.25^{cdefghijklm}$	$9.88^{bcdefghij}$	$5.34^{bcdefgh}$	$5.28^{bcdefghi}$
G26	$7.56^{defghijklm}$	$5.00^{fghijklm}$	$3.48^{efghijklm}$	0.77^{lm}
LSD (0.05)	6.710		3.970	
p-value	0.01		0.001	

Means followed by different superscripts are significantly different at $p < 0.05$.

4. Discussion

4.1. P application, Alectra vogelii and Bambara genotypes

In this study*,* *Alectra vogelii* significantly decreased by 0.40 counts due to a 20 kg P ha^{-1} difference between inoculated and non-inoculated Bambara genotypes. This could be because the P application enhanced the health of the Bambara genotypes and strengthened the host's defensive system, resulting in a decrease in the release of strigolactone. These findings imply that, in certain P-deficient soils, P addition could be necessary to promote growth and reproduction, which has not been the case in most Bambara groundnut grown in Zimbabwe. The supply of P to non-inoculated Bambara genotypes is key to supporting the vegetative stage and initiation of flowering. This study confirmed that P is critical beyond root development as it plays a significant role in Bambara growth and promotion of reproductive stage. Farmers apply nitrogen as a top dressing in crop production, which differs from the application of P as a basal dressing, but this study revealed the need to co-top dress with nitrogen and P fertilizer. Several studies have shown the importance of adding P to increase nutrient release, which affects final crop yields [29,33–35]. P and nitrogen work well in facilitating the provision of additional nutrients to Bambara genotypes in order to promote growth and development. Legumes require P as a key nutrient for root development, crop establishment, and nitrogen fixation [36,37].

Inoculated Bambara genotypes had higher chlorophyll content than the non-inoculated. Such high chlorophyll content is an adaptation or compensatory behaviour to sustain high rates of CO_2-assimilation, which serve as a defense mechanism for the Bambara genotypes against parasite infestation [38]. Gasura et al. [38] and Mandumbu et al. [18] stated that resistant/tolerant genotypes proved to adjust chlorophyll content to be independent to keep photosynthesis at an optimal rate while simultaneously supplying the parasite in the rhizosphere. This explains why high amounts of carbohydrates are transported and found in the roots of *Alectra vogelii*-infected plants, thus promoting the growth and development of the parasite. This promotes the growth and development of both the parasite and host plant [38,39]. The high chlorophyll content could have also contributed to the delayed flowers under *Alectra*-inoculation treatment causing them to increase in the number of pods and number of seeds, resulting in a positive effect on grain yield. The results were similar to Gurney et al. [40], who reported that maize varieties that had high chlorophyll under *Striga* infection also had increased the rate of photosynthesis. P fertilizer improved the nutrient status of Bambara plants, promoting good plant health, vitality, and immunity in order to supply yield under *Alectra vogelii* attack [41]. Dikr and Abayechaw [4] stated that the availability of P by the host plant increased ripeness uniformity and early maturity in legumes. It also increased the capacity of nitrogen fixation and harvest quality and increased resistance to plant diseases [4].

4.2. Interaction between P and Alectra vogelii

The higher chlorophyll content in the Bambara genotypes increased days to flowering when 20 kg P ha^{-1} was added to infected crops. According to this study, Bambara's increased chlorophyll content after *Alectra vogelii* infestation may be a compensatory tactic to help both crops and parasitic weeds to survive. This is a means of survival that ensures the development of flowers, pods, and seeds. Early flowering due to compensation following the *Alectra vogelii* infestation is similar to the behavior of plants stressed by water and nutrient deprivation [36]. Finch-Savage and Bassel [42] noted this behavior as the main aim for all living nature in the ecosystem to reproduce for the next generation's plants. When a plant reaches the peak vegetative stage and has enough stored nutrition to support grain through translocation, reproduction/survival becomes its main purpose. Consequently, this compensation approach is a significant pathway that drives survival and also from being attacked by *Alectra vogelii*. The application of P and improved host plant immune system contributed to the onset of flowering, which led to maturity governing the reproductive stage initiation. On the other hand, Lee et al. [43] stated that to maintain the survival of the species, the crop initiates its reproductive cycle early due to changes in atmospheric variables such as low soil moisture and low nutritional in the soil status. The reduction in days to flowering after P addition, suggesting the need for its nutritional supply to *Alectra*-infested plots in smallholder farming systems. The number of days to flowering was reduced after P suggests the need for its nutritional supply, which resulted in early maturity, giving farmers yield on the *Alectra*-infected crop.

There was significantly lower chlorophyll content on 20 kg P ha^{-1} compared to the control or the non-inoculated treatment. In genotypes on non-inoculated *Alectra vogelii*, the amount of chlorophyll was sufficient to promote normal growth. This is because the soil used in the study had adequate available nutrients such as P, Ca, and Mg that could support the natural growth of Bambara groundnut genotypes. In a related research, Vocciante et al. [44] and Kumari et al. [36] found that when plants experience a biotic stressor or deficiency over an extended length of time, their defenses are compromised, making them more vulnerable to pest and disease attacks, such as those by *Alectra vogelii*. The reduction of chlorophyll content in Bambara on soil infected by *Alectra* vogelii suggests that some nutrients apart from P were not taken up by the host plant. The reason for this reduction could have been influenced by the Sprengel-Liebig law of the minimum, which states that if one essential component is lacking or absent while the others are present, the soil becomes unproductive for growing crops because of that one component [45]. Key nutrients such as zinc, iron, and copper are usually limited components caused by excess P fertilizer application. The excess P fertilizer causes the nutrients to be lacking, hence leading to a decrease in chlorophyll production. Despite the suggested limitation of some key nutrients (besides P) to support chlorophyll production, Bambara groundnut immune system was improved following the addition of P fertilizer. This is because P fertilizer promoted good health, which enabled the host plant to not release strigolactones, thereby reducing *Alectra vogelii* infestation.

4.3. Interaction between P application and bambara genotypes

There was a significant decrease in days to flowering, days to maturity, and chlorophyll content after the addition of 20 kg P ha^{-1} to *Alectra*-inoculated genotypes compared with the control. The application of 20 kg ha^{-1} of P fertilizer prevented *Alectra vogelii* stimulation and attachment to Bambara genotypes. This could be due to the low response of these Bambara genotypes to P application, which could have been attributed to the fact that these landrace accessions had adapted to low-P conditions. Although legumes are typically known to have a high P demand [46], these Bambara landraces, which may have naturalized in low-P environments, showed benefits from the additional of 20 kg P ha^{-1}. According to Wafulae et al. [47] and Khojely et al. [34], landraces require little extra mineral P fertilizer to generate a relatively high yield. According to Irfan et al. [48] Bambara genotypes AEM-40 and 30 had similar genes for high grain yields but were highly efficient in terms of P utilization.

Musango et al. [39] found that applying an additional P fertilizer at 20 kg ha^{-1} increased the weight and yield of Bambara groundnut pods. In contrast, non-P treatments decreased the cowpea yield by 7.9 % under *Alectra vogelii* infestation [49]. David et al. [50] found that *Striga* infestation results from the insufficient application of P and nitrogen by farmers, which is consistent with the findings of the present study. According to Irsyadi et al. [51], genetic diversity among landraces resulted in varying responses to *Alectra vogelii* in terms of yield components.

4.4. Interaction between bambara genotypes and Alectra inoculation

The results showed that *Alectra vogelii* reduced the yield of genotypes G23, G24, and G25, which had low yields and yield components. The attachment of parasitic weeds to the host plant, which reduces carbon transfer to shoot biomass, causes this decrease. The results of Phiri et al. [30] and Dieni et al. [31] documented comparable declines in pod weight, number of pods per plant, number of seeds per pod, seed weight, and chlorophyll content following *Alectra vogelii* infestation that were validated by these data. However, in this study, Bambara genotype G10 demonstrated tolerance to *Alectra vogelii* infection, resulting in a much higher grain yield.

Dieni et al. [31] stated that several genes that regulate different aspects of resistance are likely to be responsible for the persistence and sustainable tolerance of host crops to *Alectra vogelii*. The genotypes G23, G24, and G25 exhibit greater tolerance, or at least some degree of tolerance, towards *Alectra vogelii* in comparison to other genotypes. According to Mwangangi et al. [52], grain production is believed to be one of the crop growth traits that makes it extremely vulnerable to parasite weed invasion. Bambara genotypes G9, G18, and G21 did not produce *Alectra vogelii* shoots and had high yields, indicating that they may be the most promising genotypes resistant to *Alectra vogelii*. These genotypes have shown their ability to withstand *Alectra vogelii's* infection by continuing to produce yield, despite the parastic attack [39]. Bambara's genetic traits are crucial for enhancing food security. However, the Mana variety, examined in this study, proved susceptible to *Alectra vogelii* and is therefore, unsuitable for production in *Alectra*-infested soils.

5. Conclusion

This study demonstrates that the application of P fertilizer effectively suppresses *Alectra vogelii* stimulation and attachment to Bambara plants. Specifically, application of 20 kg P ha^{-1} resulted in the suppression of *Alectra vogelii*, leading to a reduction in the number of days of flowering, days to maturity, and chlorophyll content in both inoculated and non-inoculated Bambara genotypes. P contributed to enhanced yield in *Alectra*-inoculated Bambara genotypes. Genotypes G23, G24, and G25 displayed tolerance to *Alectra vogelii* and showed the ability to utilize P for growth and development. These genotypes are promising germplasm sources for breeding purposes. The results showed that applying P at a rate of 20 kg P ha^{-1}, along with identifying resilient genotypes such as G23, G24, and G25 effectively reduced *Alectra vogelii* infestation and resulted in higher yields. Further field evaluation of this experiment is recommended to check on impact natural infestation and P interactions.

CRediT authorship contribution statement

Rudo Musango: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tamado Tana:** Writing – review & editing, Validation, Supervision. **Stanford Mabasa:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis. **Edmore Gasura:** Writing – review & editing, Visualization, Validation, Supervision, Software. **Josephine Tafadzwa Pasipanodya:** Writing – original draft, Methodology, Investigation, Conceptualization. **Ronald Mandumbu:** Writing – review & editing, Visualization, Validation, Supervision. **Tonny Phirilani Tauro:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Data availability statement

All the data is included within the manuscript and supplementary materials.

Consent for publication

All the authors read the manuscript and agreed with its contents for publication.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used [Paperpal, QuillBot and Grammarly / grammar check] in order to [improve language and readability, with caution]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Funding statement

The Africa Center of Excellence for Climate Smart Agriculture and Biodiversity Conservation under Haramaya University, Ethiopia, in collaboration with the World Bank, provided scholarship under grant IDA Credit 5794-ET.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Special thanks go to the Crop Breeding Institute and Genetic Resources and Biotechnology Institute for providing Bambara groundnut genotypes and Henderson Research Station (The Weed Team) for providing technical assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40973.

References

[1] High level Panel of Experts, Food security and nutrition: building a global narrative towards 2030. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome, 2020.

[2] Z. Tadele, Raising crop productivity in Africa through intensification, Agronomy 7 (2017) 22, https://doi.org/10.3390/agronomy7010022, 2017.

[3] S. Praharaj, M. Skalicky, S. Maitra, P. Bhadra, T. Shankar, M. Brestic, et al., Zinc biofortification in food crops could alleviate the zinc malnutrition in human health, Molecules 26 (12) (2021) 3509, 2021.

[4] W. Dikr, D. Abayechaw, Effects of phosphorus fertilizer on agronomic, grain yield and other physiological traits of some selected legume crops, Journal of Biology, Agriculture and Healthcare 12 (No.12) (2022) 2022.

[5] S. Tiwari, C. Lata, P.S. Chauhan, C.S. Nautiyal, Pseudomonas putida attunes morpho-physiological, biochemical and molecular responses in *Cicer arietinum* L. during drought stress and recovery, Plant Physiology Biochemistry 99 (2016) 108–117.

[6] A. Tomer, S.K. Singh, Drought stress tolerance in legume crops, in: In Agronomic Crops, Springer, Singapore, 2020, pp. 149–155, 2020.

[7] J.T. Pasipanodya, L.N. Horn, E.G. Achigan-Dako, R. Musango, J. Sibiya, Utilization of plant genetic Resources of Bambara groundnut conserved ex situ and genetic diversification of its primary genepool for semi-arid production, Agriculture 12 (2020) 492, https://doi.org/10.3390/agriculture12040492, 2022.

[8] J. Mubaiwa, V. Fogliano, C. Chidewe, E.J. Bakker, A.R. Linnemann, Utilization of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) for sustainable food and nutrition security in semi-arid regions of Zimbabwe, PLoS One 13 (10) (2018) e0204817.

[9] D. Mwenye, R. Musango, O. Chipfunde, Characterisation and biodiversity conservation of Bambara nuts (*Vigna subterranea)*: experiences from mutoko district of Zimbabwe. 10th Zimbabwe International Research Symposium, 2015.

[10] S. Mayes, W.K. Ho, H.H. Chai, B. Song, Y. Chang, F. Massawe, Bambara groundnut (*Vigna subterranean* (L.) verdc.) A climate Smart crop for food and nutrition security, in: Genomic Designing of Climate-Smart Pulse Crops, Springer, Berlin, 2019, pp. 397–424.

[11] Food and Agriculture Organization of the United Nations, Fertilizer Use by Crops in Zimbabwe, First Version, Published by FAO, Rome, 2006, 2006.

[12] N.S. Tlankka, E.R. Mbega, P.A. Ndakidemi, Potential of indigenous pesticidal plants in the control of field and post-harvest arthropod pests in Bambara groundnuts (*Vigna subterranea* (L.) Verdc.) in Africa: a Review, Am. J. Plant Sci. 11 (2020) 745–772.

[13] X.L. Tan, S. Azam-Ali, E. Von Goh, M. Mustafa, H.H. Chai, W.K. Ho, S. Mayes, T. Mabhaudhi, S. Azam-Ali, F. Massawe, Bambara groundnut: an underutilized leguminous crop for global food security and nutrition, Front. Nutr. 7 (2020) 276, 2020.

[14] M. Fernández-Aparicio, P. Delavault, M.P. Timko, Management of infection by parasitic weeds. A review, Plants 9 (2020) 1184, https://doi.org/10.3390/plants9091184.

[15] B. Zwanenburg, A.S. Mwakaboko, C. Kannan, Suicidal germination for parasitic weed control, Pest Manag. Sci. 72 (2016) 2016–2025.

[16] J.R. Qasem, Weed Seed Dormancy: the Ecophysiology and Survival Strategies. Seed Dormancy and Germination, IntechOpen, 2019. https://www.intechopen.com/chapters/68647.

[17] C.K. Phiri, V.H. Kabambe, J. Bokosi, An insight of parasitic weeds in Africa and scientific developments: a review, J. Bot. Res. 5 (2023) 59–75.

[18] R. Mandumbu, C. Mutengwa, S. Mabasa, E. Mwenje, Challenges to the exploitation of host plant resistance for *Striga* management in cereals and legumes by farmers in sub-Saharan Africa: a review, Acta Agric. Scand. Sect. B Soil Plant Sci 69 (1) (2019) 82–88, https://doi.org/10.1080/09064710.2018.1494302.

[19] V. Namutebi, L.N. Mulumba, J. Bisikwa, Evolution of cereal-legumes cropping on *Striga* control and maize yield, J. Agric. Sci. Technol. B10 (2020) 43–48.

[20] G. Brun, L. Braem, S. Thoiron, K. Gevaert, S. Goormachtig, P. Delavault, Seed germination in parasitic plants: what insights can we expect from strigolactone research? J. Exp. Bot. 69 (2018) 2265–2280.

[21] R. Mandumbu, C. Mutengwa, S. Mabasa, E. Mwenje, J. Gotosa, V. Munyati, The parasitic weeds scourge in northern Zimbabwe: effects of soil degradation, hosts and food security implications to rural farmers, Sciences 20 (2017) 86–91, https://doi.org/10.3923/jbs.2017.194.201.

[22] W. Makaza, J.T. Rugare, S. Mabasa, E. Gasura, O.V. Gwatidzo, R. Mandumbu, In vivo and in vitro performance studies on groundnut (*Acharis hypogea* L.) genotypes for yellow witchweed (*Alectra vogelii* Benth.) resistance, Journal of Current Opinion in Crop Science 2 (2021) 165–177.

[23] C. Njekete, J. Midzi, N. Bhekumthetho, M. Tendai, Response of *Alectra vogelii* Benth to different crop root exudates, International Journal of Plant and Soil Science 15 (2017) 1–12.

[24] R. Musango, J.T. Pasipanodya, T. Tamado, S. Mabasa, W. Makaza, *Alectra vogelii*: a threat to Bambara groundnut production under climate change: a Review Paper, J. Agric. Chem. Environ. 11 (2) (2022), 2022.

[25] S. Mutsvanga, E. Gasura, P.S. Setimela, C.S. Nyakurwa, S. Mabasa, Nutritional management and maize variety combination effectively control *Striga asiatica* in southern Africa, CABI Agriculture and Bioscience 3 (1) (2022) 1–14, https://doi.org/10.1186/s43170-022-00108-4.

[26] R.K. Ojha, S.K. Jha, Role of mineral nutrition in management of plant diseases, in: H.K. Singh, S.S. Solankey, M.K. Roy (Eds.), Farmers' Prosperity through Improved Agricultural Technologies, Jaya Publishing House, New Delhi, 2021, pp. 241–261.

[27] M. Jamil, F.K. Kanampiu, H. Karaya, T. Charnikhova, H.J. Bouwmeester, *Striga hermonthica* parasitism in maize in response to N and P fertilisers, Field Crops Res. 134 (2012) 1–10.

[28] V.H. Kabambe, J.M. Bokosi, Role of variety and fertilizer practices on cowpeas (*Vigna unguiculata*) yield and field incidence of the parasitic weed *Alectra vogelii* (Benth) in Central Malawi, J. Agric. Sci. 12 (11) (2020) 200.

[29] T.P. Tauro, F. Mtambanengwe, S. Mpepereki, P. Mapfumo, Soil fungal community structure and seasonal diversity following application of organic amendments of different quality under maize cropping in Zimbabwe, PLoS One 16 (10) (2021) e0258227, https://doi.org/10.1371/journal.pone.0258227.

[30] C.K. Phiri, V.H. Kabambe, J. Bokosi, P. Mumba, Screening for resistance mechanisms in cowpea genotypes on *Alectra vogelii*, Am. J. Plant Sci. 4 (6) (2018) 1362–1379, 9.

[31] Z. Dieni, J.B.D.L.S. Tignegre, P. Tongoona, D. Dzidzienyo, I.K. Asante, K. Ofori, Identification of sources of resistance to *Alectra vogelii* in cowpea *Vigna unguiculata* L. Walp germplasm from Burkina Faso, Euphytica 21412 (2018) 234, 10.1007/s10681-018-2311-3.

[32] W. Wondimu, T. Tana, Yield response of common bean (Phaseolus vulgaris L.) varieties to combine of nitrogen and phosphorus fertilizers at Mechara, Eastern, J. Plant Biol. Soil Health 4 (2) (2017) 7.

[33] H. Nezomba, F. Mtambanengwe, R. Chikowo, P. Mapfumo, Sequencing integrated soil fertility management options for sustainable crop intensification by different categories of smallholder farmers in Zimbabwe, Exp. Agric. 51 (1) (2015) 17–41, 2015.

[34] D.M. Khojely, S.E. Ibrahim, E. Sapey, T. Han, History, current status, and prospects of soybean production and research in sub-Saharan Africa, Crops Journal (6) (2018) 226–235, https://doi.org/10.1016/j.cj.2018.03.006.

[35] T.P. Tauro, H. Nezomba, F. Mtambanengwe, P. Mapfumo, Increasing phosphorus rate alters microbial dynamics and soil available P in a Lixisol of Zimbabwe, PLoS One 18 (9) (2023) e0291226.

[36] V.V. Kumari, P. Banerjee, V.C. Verma, S. Sukumaran, M.A.S. Chandran, K.A. Gopinath, G. Venkatesh, S.K. Yadav, V.K. Singh, N.K. Awasthi, Plant nutrition: an effective way to alleviate abiotic stress in agricultural crops, International Journal of Molecular Science 23 (2022) 8519, https://doi.org/10.3390/ijms23158519, 2022.

[37] C. Pisa, D. Sibanda, X. Poshiwa, T.P. Tauro, The effect of ridging and phosphorus application on Neorautanenia brachypus (Harms) vegetative growth and tuber development, in: Climate Change Adaptations in Dryland Agriculture in Semi-arid Areas, Springer Nature Singapore, Singapore, 2022, pp. 261–272.

[38] E. Gasura, P. Setimela, S. Mabasa, R. Rwafa, S. Kageler, C. Nyakurwa, Response of IITA maize inbred lines bred for *Striga hermonthica* resistance to *Striga asiatica* and associated resistance mechanisms in southern Africa, Euphytica 10 (2019) 1–15.

[39] R. Musango, T. Tana, S. Mabasa, E. Gasura, J.T. Pasipanodya, R. Mandumbu, T.P. Tauro, Interactions of Bambara groundnut (*Vigna subterranean* (L) Verdc) genotypes and phosphorus fertilizer rates in controlling, Alectra vogelii Cogent Food & Agriculture, Soil & Crop Sciences Journal 0 (1) (2024) 2416499, https://doi.org/10.1080/23311932.2024.2416499.

[40] A. Gurney, M. Press, J. Scholes, Infection time and density influence the response of sorghum to the parasitic angiosperm *Striga hermonthica*, New Phytol. 143 (1999) 573–580, https://doi.org/10.1046/j.1469-8137,1999.00467.x.

[41] R. Tripathi, R. Tewari, K.P. Singh, C. Keswani, T. Minkina, A.K. Srivastava, U. De Corato, E. Sansinenea, Plant mineral nutrition and disease resistance: a significant linkage for sustainable crop protection, Front. Plant Sci. 13 (2022) 883970, https://doi.org/10.3389/fpls.2022.883970.

[42] W.E. Finch-Savage, G.W. Bassel, Seed vigour and crop establishment extending performance beyond adaptation, Journal of Experiment Botany 67 (3) (2015) 567–591.

[43] E.P. Lee, Y.S. Han, S.I. Lee, K.T. Cho, J. Park, Y. You, Effect of nutrient and moisture on the growth and reproduction of *Epilobium hirsutu*m L., an endangered plant, Journal of Ecology Environment 41 (2017) 35, https://doi.org/10.1186/s41610-017-0054-z, 2017.

[44] M. Vocciante, M. Grifoni, D. Fusini, G. Petruzzelli, E. Franchi, The role of plant growth-promoting rhizobacteria (PGPR) in mitigating plant's environmental stresses, Appl. Sci. 12 (2022) 1231, https://doi.org/10.3390/app12031231.

[45] R.R. Van der Ploeg, W. Bohm, M.B. Kirkham, Theory of mineral nutrition of plants and the Law of the minimum, Soil Sci. Soc. Am. J. 36 (5) (1999) 1055–1062, https://doi.org/10.2136/ssaj/1999.6351055x.

[46] O.M. Oluwakemi, O. Folashade, F.M. Owoade, Response of cowpea varieties to sources are rates of phosphorus in Ogbomoso, Global Scientific Journals 9 (2021). Issue 10.

[47] J.S. Wafula, B.O. Nyongesa, B.A. Were, S. Gudu, Genotypic variation of Bambara groundnut (*Vigna subterranea* L.Verdc) for phosphorus efficiency, Acta Agric. Scand. Sect. B Soil Plant Sci 71 (1) (2021) 68–80, https://doi.org/10.1080/09064710.2020.1850852.

[48] M. Irfan, J.A. Shah, M. Abbas, Evaluating the performance of mung bean genotypes for grain yield, phosphorus accumulation and utilization efficiency, J. Plant Nutr. 40 (19) (2017) 2709–2720.

[49] I.E. Magani, S.T.O. Lagoke, A.M. Emechebe, Effect of nitrogen and P application on the reaction of cowpea to the parasitic *Alectra vogelii*, Journal of Applied Biosciences 10 (2008) 500–506, 2008.

[50] O.G. David, A.S. Ayangbenro, J.J.O. Odhiambo, O.O. Babalola, *Striga hermonthica*: a highly destructive pathogen in maize production, Environmental Challenges 8 (2022) 3667, https://doi.org/10.1016/j.envc.2022.100590, 0100.

[51] M.B. Irsyadi, S.K. Sari, E. Oktiastuti, I.A. Rineksane, Rapid genomic DNA extraction for Soybean (*Glycine max* L. Merr) using modified CTAB protocol to obtain high-quality DNA, Indian J. Biochem. Biophys. 61 (2) (2024) 97–104, https://doi.org/10.56042/ijbb.v61i2.7603.

[52] I.M. Mwangangi, L. Büchi, S.M. Haefele, J. Rodenburg, Macronutrient application rescues performance of tolerant sorghum genotypes when infected by the parasitic plant *striga*, Ann. Bot. 1 (2024) mcae031.