

# *Alectra vogelii*: A Threat to Bambara Groundnut Production under Climate Change: A Review Paper

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## Abstract

Bambara groundnut (BGN) is a protein-rich pulse with the ability to lead to more climate-resilient agriculture. The objective of this study was to review *Alectra vogelii* as a potential threat to BGN production as a result of climate change. However, the crop faces biotic and abiotic stresses. *Alectra vogelii* is a major biotic constraint to BGN production, especially in Africa's non-fertile semi-arid regions. *Alectra vogelii* (L.) Benth is a parasitic weed in the Orobanchaceae family that causes major damage by forming haustoria attached to roots to enable absorption of nutrients from the BGN. *Alectra vogelii* produces a large number of minute seeds that can live in the soil for up to 20 years. Based on the reviewed literature, various control mechanisms for dealing with the harmful effects of *Alectra vogelii* have been proposed. The aim of this research was to reveal the effect of *Alectra vogelii* on BGN and possible control strategies. We discuss the different control methods such as cultural and mechanical management procedures, phosphorus fertilizers and resistant host crops, herbicide use, and integrated *Alectra vogelii* control methods. In adaptive methods, however, new techniques remain important. The life cycle of root parasitic weeds is inextricably linked to that of their host, making it an ideal target for such new control techniques, especially when aimed at the early stages of the host-parasite relationship. This review reveals additional information on the function of parasitic seed, strigolactones and how they can be used in breeding to management parasitic weeds.

## Keywords

Global Climate Change, *Alectra vogelii*, Strigolactones, Parasitic Weed, Bambara Groundnut, Host Plant Resistance, Control Strategies

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## 1. Introduction

The risk to global food security due to climate change (leading to drought, desertification, salinization, flooding and increased temperature), population expansion and also urbanization has been referred to as one among the biggest challenges facing humankind during this twenty-first century [1]. There are significant concerns that the yield increases likely for a smaller number of staple crop species, predominantly major cereals, (wheat [*Triticum spp.*], rice [*Oryza sativa*] and maize [*Zea mays*]) that have provided food through the green revolution for the previous four decades, Harlan [2] would not be adequate to feed an expanding global population in the face of climate change [3]. Exploiting underutilized crop plants with diverse genetic resources and potentially beneficial traits is regarded as one of the options that could include a more diverse agricultural system and additional food supplies, all of which are needed to address food and nutrient security issues [4]. Bambara groundnut (BGN) is an important crop within the developing world and specifically in Africa, because of its ability to yield with minimal inputs in drought-prone environments [5].

The crop is an indigenous African legume, that is predominantly within the traditional farming systems and is mainly used in all places in the country as an intercrop of cereals and other crops. BGN is a pulse crop with immense potential in enhancing food security, in the African farming community because of its ability to yield in low-input agricultural on marginal land and on poor, free draining soil. BGN as a legume, fixes atmospheric nitrogen and contributes to soil fertility Sprent *et al.* [6], while nutritional it complements cereal crops such as maize (*Zea mays*) and sorghum (*Sorghum bicolor*) [7]. BGN seed contains 18% - 24% protein with high lysine and methionine, 51% - 70% carbohydrate, 4% - 12% crude oil, 3% - 5% ash and 3% - 12% fibre [7]. BGN is additionally rich in iron 4.9 - 48 mg/100g compared to a range of 2.0 - 10.0 mg/100g for many food legumes, potassium 11.44 - 19.35 mg/100g, sodium 2.9 - 12.0 mg/100g, and calcium 95.8 - 99 mg/100g. The crop has approximately 367 - 414 kal/100mg energy [8]. The gross energy value of BGN seed is higher than that of other legumes [9].

Research done by Olukolu *et al.* [10], provided evidence that Cameroon and Nigeria as the center of origin for Bambara groundnut, used both phenotypic descriptor and DArT markers. In Africa, the yield ( $\text{t}\cdot\text{ha}^{-1}$ ) of BGN varies among landraces and location with yield potential exceeding  $3 \text{ t}\cdot\text{ha}^{-1}$  [8]. Berchie *et al.* [11] discovered that BGN yields of up to  $4 \text{ t}\cdot\text{ha}^{-1}$  were obtained in some landraces where temperatures were high and rainfall was poor in Ghana's transition agro-ecological region. BGN has the potential to provide food security within

the dry areas. According to IPCC [12] BGN (legumes) is estimated to benefit from moderate climate change, although the effect could be highly variable across varieties [12]. In this article, the main objective was to review *A. vogelii* as a potential threat to Bambara groundnut production as a result of climate change. The life cycle of root parasitic weeds is inextricably linked to that of their host, making it an ideal target for such new control techniques, particularly when targeting at the early stages of the host-parasite relationship. Most of the parasitic weed control strategies are based on *Striga* species, and there is not much information concerning *Alectra vogelii*. Therefore, what could be happening to *Striga* could also be extended to *Alectra vogelii*. Hence, studies would be desperately needed in this regard.

## 2. Hosts/Species Affected with *Alectra vogelii*

The parasitic angiosperm *A. vogelii* (Benth) is a hemi-parasitic weed belonging to Orobanchaceae family [13]. *A. vogelii* includes about 30 species occurring primarily in tropical and subtropical Africa [14]. Olmstead *et al.* [15] stated that the sequence analysis of three plastids suggested that these belonged to the Orobanchaceae family along with closely related parasitic genera. *A. vogelii* species are C3 weeds similar to *Striga* species but have broader leaves and yellow flowers, attack broad-leafed hosts as well as most of the leguminous species in the sub-Saharan Africa, Southern and Eastern Africa [13] [16]. Its hosts are specifically in crops of Fabaceae and Asteraeae families [17]. The weed causes significant crop losses in cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*) in Africa, but other high crop losses have been reported in Botswana, Ethiopia and Mali [14]. Other leguminous crops are Bambara groundnut (*Vigna subterranean*), mung bean (*Vicia radiate*), common bean (*Phaseolus vulgaris* L.), chickpea (*Cicer arietinum*), soyabean (*Glycine max* L.) are also damaged in parts of eastern and southern Africa. Cover crops attacked by *A. vogelii* include *Indigofera* and *Tephrosia species*, lablab (*Lablab purpureus*). It can also parasitize a number of non-legume weeds which include beach hibiscus (*Hibiscusmeusei*) (Malvaceae), spurge (*Euphorbiaceae*), upright stabur (*Acanthospermum hispidum*), pigweed (*Amaranthus palmeri* S. Wats) and (*Vernonia poskeana*) Compositae species [18]. This wide range of hosts poses a problem for the introduction of alternative pulses or legume cover crops into arable rotation.

*A. vogelii* has a wide distribution range that extends from the Northern Province of South Africa and Swaziland, through central Africa to Burkina Faso and Mali in West, through Tanzania and Kenya to Ethiopia in the east [19]. The *A. vogelii* races from West Africa and Cameroon attack cowpea and groundnut, those from Botswana and northern part of South Africa attack mung bean, while those from Kenya, Malawi, and Zimbabwe attack BGN in addition to the other crops which are susceptible elsewhere [20]. The above information can be used for breeding programs and production hence promoting trade within Africa on these legumes and for evaluating the different *Alectra* strains from these differ-

ent countries.

### 3. Effect of *A. vogelii* on Host Plants

*A. vogelii* causes serious damage to legume crops and on other non-legumes causing high food insecurity and malnutrition in various part of the sub-Saharan and Eastern Africa [13] [16]. The seed germinates upon induction by exudate from the host plant roots, which is either alectrol or other strigolactones [18]. *A. vogelii* has been observed in Bambara groundnut (*Vigna subterranean* (L) Verdc.), cowpea (*Vign unguiculata* (L.) Walp), soyabean (*Glycine max* (L) Merr.), mung bean (*Vigna radiate* (L.) and common bean (*Phaseolus vulgaris* L.) [21]; [18]. It is expected that the rapid spread of this parasitic weed and the enormous yield reduction Karanja *et al.* [21] it causes would constitute a severe threat to legume production. The widespread incidence of *A. vogelii* on cowpea presents severe challenges on smallholder farmers with a record of yield reduction up to 100% [21].

In Botswana yield losses of up to 80% to 100% in a highly susceptible cowpea cultivar Black-eye Phiri *et al.* [18] were recorded while in Tanzania yield losses of up to 50% have been reported [22]. In Nigeria a yield loss of up to 15% was reported in groundnut. BGN as crop of resource-poor households been affected by *A. vogelii* [21], and this impose an additional stress on farmers who have little capacity for investment in crop production, must cope in an environment characterized by marginal rainfall for cropping and declining soil fertility. BGN has traditionally been grown in multiple cropping systems within low populations of landraces are planted in mixtures with cereals. An increase in the *A. vogelii* Karanja *et al.* [21] similar to *Striga* problem in many African countries is pandemic and seems to be getting worse [23]. For instance, in the Republic of South Africa 30% - 50% reductions in yield of BGN were reported [18]. The negative effects of the weed in decreasing the vegetative and grain yield of cowpea the crop has been studied [18] [21]. According to farmer's view, losses between 80% - 100%, and have eventually enforced them to abandon highly infested fields [24]. The infestation area and level are expected to extend within the future, because of continued monoculture together with low organic, mineral fertilizer input rates and global climate change [24]. Fields infested by these parasitic weeds are difficult to clean due to their enormous reproductive capacity for example *A. vogelii* can produce 400,000 to 600,000 viable seeds per plant [25]. These seeds can remain dormant in the soil for twelve years [26]. Reports show that yield decrease is facilitated through the delayed onset of flowering, reduced number of flowers, reduced mass of pods and grain [18] [21].

### 4. *A. vogelii* under Climate Change Projection

Temperature rises, atmospheric greenhouse gas emissions, soil degradation, and competition for land and water resources will all have an influence on BGN production systems in Africa. These changes will have an impact on weed com-

munities particularly parasitic ones, and management strategies must be adjusted to account for this. Higher temperatures and limited water availability will generally advantage C4 over C3 plants (e.g. BGN). Increased CO<sub>2</sub> levels, on the other hand, will boost BGN's competitiveness against C4 weeds, which include *A. vogelii* weeds. Under parasitism of the witchweed, increased CO<sub>2</sub> levels in the atmosphere may improve BGN resistance to *A. vogelii* and other parasitic weeds, but soil degradation and more frequent droughts or floods may amplify parasite species' frequency. In the dry-land areas, besides drought tolerant, *A. vogelii* well adapted to low rainfall environments could benefit from greater variability in rainfall [27].

Infestations of *A. vogelii* are commonly associated with low soil fertility, and if climate extremes lead to increased soil degradation IPCC [28], parasitic weeds may benefit. In such a setting, improving soil conservation and fertility management becomes even more critical. Knowledge of local circumstances and an awareness of the overall system dynamics are required for the selection of appropriate soil conservation and fertility measures.

Changes in temperature will have an impact on parasitic weed distribution, with certain species particularly *A. vogelii* spreading to higher latitudes and altitudes. *A. vogelii* might, for example, expand their geographic range in this way. It may spread to mild climate zones, based on genetic understanding and ecological niche modeling. However, *A. vogelii* has been found to be largely temperature insensitive, and its dispersal may be influenced more by changes in the host crop's range than by temperature. This could be true for parasitic weeds in general, according to Phoenix and Press [29]. BGN germplasm that is heat, cold, or drought tolerant has recently been selected, enhancing the crop's ability to adapt to future environmental stress. This could help BGN grow on favorable conditions, which may cause a concomitant shift in the range of parasitic weeds.

## 5. Effect of Temperature on Weeds

The geographical range of many weeds species is largely determined by temperature and it has long been known that temperature determines effective establishment of new environments by weedy species [30]. Hellman *et al.* [31] suggested that weeds may migrate rapidly with increasing surface temperature because of their characteristics that are associated with long-distance seed dispersal. Global warming might extend the northern limits of parasitic weeds by several hundred miles [14].

*A. vogelii* is found in tropical and subtropical of Africa. Its habitat extends from South Africa throughout much of sub-Saharan Africa threatening many legume crops [14]. Dawoud and Sauerborn [32], successfully conditioned *A. vogelii* seeds over 10 days at 20°C. The optimum day/night temperatures for germination and attachment were 25/15°C and 30/25°C, respectively [14]. This was well within the range of temperatures in its African natural surroundings. Changes in temperatures from the optimum fundamentally decreased germination and attachment showing extreme sensitivity to extreme temperatures hence

showed differences in their climate adaptation.

## 6. Effect of Water Deficit

Due to climate change, drought is predicted more frequently in some regions in the future. Between 1988 and 1992, over 15 drought events have been mentioned in diverse areas of southern Africa [33]. Rainfall variability in southern Africa has confirmed extended statistical affiliation to the El Niño-Southern Oscillation (ENSO) phenomenon [33]. Before the 1980, strong El Niño's occurred on average every 10 - 20 years IPCC [33], yet, the early 1980 marked the start of a different sequence of strong El Niño events. Climate changes of this magnitude may have far reaching negative impacts on the availability of water resources and competition between plants and weeds [33].

Water transpired by way of weeds could exacerbate crop drought stress in dry periods through growing soil moisture deficits, resulting in a lower in crop water use efficiency (WUE). For example, in cluster bean (*Cyamopsis tetragonoloba*), water intake was higher in unweeded plots, WUE reduced with the increase in time of weed elimination beyond 20 days after crop sowing [14]. Hence, weed control will become even greater crucial in drought circumstances.

Mohamed *et al.* [14] stated that *A. vogelii* germination was significantly affected by conditioning period and osmotic potential, with low and extremely variable within the growing season. These low rainfall areas are found in the sub-Saharan regions. *A. vogelii* is sensitive to low moisture, which restricts its spread northwards, especially into the semi-arid tropics, where rainfall is low and extremely variable within the growing season. Mohamed *et al.* [14]; IPCC [33] predicated that *A. vogelii* would thrive in wet tropical South American and South Asia, as the case with most *Striga* species. Mohamed *et al.* [14], reported that *A. vogelii* is also sensitive to oxygen deficiency which limits its spread in soils with poor permeability and bad drainage. Thus its spread could be confined savanna regions with regular rainfall and permeable soils, as has been observed in Mali and Ethiopia by [34].

## 7. Effect of Elevated CO<sub>2</sub>

Atmospheric CO<sub>2</sub> has risen from about 260 parts per million (ppm) 150 years ago to 380 ppm today [33]. In agriculture where both C3 and C4 weed species occur there is a wide range of responses among these species to recent CO<sub>2</sub> levels [33]. Many weeds respond positively to elevated CO<sub>2</sub> due to decreased stomatal conductance and subsequent improvements in water-use efficiency [30]. C3 plants types are likely to respond more strongly than C4 plants types to CO<sub>2</sub> increases through biomass and leaf area increase [30].

*A. vogelii* is a C3 weed species similar to *Striga hermonthica* and *Striga asiatica*. Previous research done by Watling and Press [35] on the effects of *S. hermonthica* and *S. asiatica* on their host has found out that removal of mineral nutrients, water and carbon compound alone cannot account for lower host bio-

mass and that impaired photosynthetic performance of the host is often associated with lower vigor. Further investigations in 1989 by Graves *et al.* [36] observed that *S. hermonthica* association, up to 80% of the difference in biomass between infected and uninfected plants could be attributed to lower amounts of carbon fixed by infected cereals as opposed to direct losses of carbon to the parasite. The mechanism by which host photosynthesis is affected is not clear but the effects of the parasite, on both growth and photosynthesis, can be detected even before its emergence above-ground [37]. According to Frost *et al.* [38] plants infested with parasitic weeds often exhibit lower stomatal conductance than uninfested plants which contribute to observed reductions in rates of photosynthesis.

The main impact of the parasite on host photosynthesis is via a lowering of host stomatal conductance or impairment of photosynthetic metabolism, future increases in atmospheric CO<sub>2</sub> may ameliorate these effects. Further, under conditions of elevating CO<sub>2</sub> the low photosynthetic rates typical of the parasite (C3 plant) may rise, thus reducing the demand for host carbon [33]. Although carbon relations play a central role in the relationship between *Striga* and its host, this does not exclude the possible impact of elevated atmospheric [CO<sub>2</sub>] on the other aspects of the host-parasitic association which will undoubtedly be complex, involving direct and indirect effects on both partners in the relationship; for example, increases in root growth under elevated [CO<sub>2</sub>], which has been reported for many species Watling and Press [35] may affect germination and attachment of *Striga*.

## 8. Life Cycle of *A. vogelii*

The life cycle of *A. vogelii* is alleged to be closely linked to the host plant. Unlike the *Striga* species that are responsive after a pre-incubation period of moist and suitable temperatures, *A. vogelii* does not require an after-ripening period, and hence, *A. vogelii* can immediately germinate after harvest [39]. *Alectra* seed germination is dependent on signalling molecules known as strigolactones. Under mineral nutrient deficiency host plants secrete these strigolactones into the rhizosphere to stimulate the symbiotic relationship with arbuscular mycorrhizal fungi that can help to overcome nutrient deficiency [40].

There are crucial prerequisites to successful germination that is pre-conditioning and therefore, the presence of a strigolactone produced by the host [14]. The *A. vogelii* does not germinate within the absence of pre-conditioning [14]. Preconditioning should ideally be at 30°C and germination is not significantly reduced by extending the preconditioning period from 10 to 25 days [14]. Parasitic plants will use the strigolactones to detect the presence of a suitable host. *A. vogelii* seed have the potential to germinate throughout the wet season. Once maximum sensitivity for seed germination has been achieved, that condition is maintained for an additional 30 days under warm conditions [14]. In the absence of strigolactone stimulant, the seeds will gradually resume their dormant state [41].

Once the *A. vogelii* seed has been preconditioned the seeds are then ready for

germination provided they are acceptable to the strigolactone present. Strigolactone is often produced by both the host and non-host plant. Upon germination, a germ tube, which is in vicinity to the host roots elongates towards the root of the host, develops an organ of attachment; the haustorium which assists as a connection between the parasite and its host [42]. Growth occurs largely at the meristem during the germination of the seed, this results in seedlings with elongated radicle [14]. A maximum radical elongation of 3 mm in eight days has been recorded [14].

The elongations of the radicle show a chemotropic reaction to a concentration gradient of root exudates. *A. vogelii* radicles stimulate profuse root development by the host and form a larger haustorium than *Striga*. The haustorium is used to withdraw from the host water, mineral, nutrients and carbohydrates, causing drought stress and wilting of the host [43]. Stunted shoot growth, leaf chlorosis and reduced photosynthesis are also phenomena that have been observed on susceptible host plants that contribute to the reduction of grain yield [43]. Not all the seeds in soil will be reached by strigolactone, but can remain viable for up to 20 years, forming a seed reservoir for the next cropping seasons [41].

After some weeks of underground development *A. vogelii* emerges above the soil surface. It starts to flower and produces seeds after some period of time. One plant can produce seeds up to 100,000 or more, thus can result in re-infestation of a field [13]. If the host plants are continuously grown this could result in seed population within the soil increase thus the cropping of the plants can become an uneconomical [44].

## 9. Control Strategies

No single management option can be utilized to control these parasitic weeds effectively across locations and time [45]. Vast regions of new territory are vulnerable to invasion if care is not taken to limit the infestations [46]. The optimum means to address parasitic weeds is through an integrated approach, employing a selection of measures in an intensive way [42]. Root parasitic plant control techniques can be divided into two categories: control through enhanced germination and through reduced germination. Some of the control practices are recommended by IPCC [33] to overcome the problem of land degradation for example, reduced tillage, inter-cropping, crop rotation, planting of catch crops and integrated soil fertility management. These agronomic practices can alter the carbon balance significantly by increasing organic input from litter and roots into the soil [33].

## 10. Trap and Catch Crop

Trap-crops cause suicidal germination of the parasitic weeds, hence results in seed bank depletion from the soil [47]. Crops like sunflower, okra, sorghum, and cowpeas (trap crops), can deplete parasitic weed in the soil. The crops can be intercropped with legumes to facilitated suicidal germination of *Alectra* in the soil

at the same time improving soil fertility. A susceptible crop can be grown in the infected fields but would not allow the parasite weed to flower. The crop must be plowed back into the soil killing the seedling that would have attached to the crop hence reducing the *Alectra* seed from the field [48]. The selection of effective catch crop varieties must be used to get effective results.

Catch crops are susceptible crops with high strigolactones that results in high germination rate of *Alectra* seeds, the crop is plowed back into the soil before *Alectra* flowers to cause dispersal stage. This method reduces the parasite seed bank in the same manner as the trap crop. From the research studies done, it can be concluded that catch crops can be grown continuously for three years resulting in the depletion of *Alectra* population from the field. Important crops that are potential catch crops for *A. vogelii* control are Faba bean, cowpeas, Berseem clover (*Trifolium alexandrinum*) and groundnuts [48]. According to Rodenburg [49] the activities of trap and catch crops of inducing suicidal germination of the parasite seeds is an effective measure to reduce the parasite as the seeds do not live to produce plants which can replenish the weed population. The trap and catch crop can improve arbuscular mycorrhizal colonization, with corresponding improvement in plant growth and fitness, hence increase crop yield [50].

## 11. Strigolactones Hormones as a Strategy for Parasitic Weed Control

Genetic variation in SLs responses provides an opportunity to breed plants with superior nutrient use efficiency and the ability to form symbiotic associations [51]. Reduction of parasitic plant seed germination could be a strategy for parasitic weed control [41]. In pea, field screening for resistance against *Orobanche crenata* resulted in the identification of a partially resistant cultivar that exudes lower amounts of strigolactones [41]. According to Yaoneyame *et al.* [52], in the case of sorghum, *Striga* susceptible cultivars produced large amounts of 5-deoxystrigol than did *Striga* resistant cultivars. Low germination-based resistance can also be achieved through the type of strigolactone that is exuded. For instance, in sorghum, the resistant genotype SRN39 was found to exude orobanchol instead of the 5-deoxystrigol that is exuded by susceptible cultivars [41]. Plant breeders can develop superior strigolactone analogs that can be used to stimulate suicidal germination of parasitic seeds in the soil before the crop is planted. Strigolactone research is very important to help address some challenges in weed control and management.

## 12. Synthetic Suicidal Germination

Chemicals can be used to induce suicidal germination to parasitic weeds. Natural compounds and man-made methods have been researched for their ability to induce germination. Two analogs of strigol that have been synthesized are Nijmegen-1 or GR24 (Figure 2) [45]. These synthetic strigolactone analogues Nijmegen-1 and GR24 are both active at low concentrations, showing that they

could be used to induce suicidal germination by treating the soil before the crop is sown [53]. The application of these synthetic strigolactones in the field has not been successful, because of the variability of the compound, especially on alkaline soils and also lack of and the high cost of producing large quantities of these compounds, have so far prohibited their commercial use in agriculture [24]; [46]. These synthetic SLs, must be more stable than the natural SLs to be effective.

### 13. Chemical Inhibitors

There are several herbicides that are available for controlling *Striga* infestation in sorghum and maize [54]. There are two general categories that is, pre emergence and post-emergence. On root parasitic weeds, the main crop damage is done during the underground parasitic life stages and therefore pre-emergence herbicides that are capable of controlling these parasitic weeds which include dinitroanilines (DNA's), Diphenyl/ethers, glyphosate and imazamox are effective on Orbanche/Phelipanche root parasitic weeds [37]. Post-emergence herbicides are systemic herbicides that are applied to the crop foliage and delivered to the shoot or root parasites either via the haustorium or through exudation to the rhizosphere from the crop roots [37]. The systemic herbicides used for parasitic weeds include inhibitors of aromatic (glyphosate) or branched-chain amino acid synthesis (imidazolinones and sulfonylureas), inhibitors of vitamin folic acid (asulam), inhibitors of glutamine synthetase (glufosinate), or hormonal herbicides (2,4-D and dicamba) [37]. These chemicals can be applied on *A. vogelii* for they are similar in their developmental stages.

Seed dressings can be effectively used to prevent attacks. Commercial seed treatments with fungicides and insecticides are normally utilized in modern agriculture. Herbicide, seed treatments could be of interest for instance root parasite infections will be killed on the root system of the host plants. Herbicide seed treatments with two acetolactate synthase inhibiting herbicides, the sulfonylurea herbicide nicosulfuron and the imidazoline herbicide imazaquin, have been effective in controlling *S. hermonthica* in maize and sorghum [55]. Seed treatments with the imidazolinones have proven to be effective in controlling other legumes crops such as *O. crenata* in faba bean and lentil and *S. generioides* and *A. vogelii* on cowpeas [55]. Magani and Lagoke [56], revealed that farmers can reduce cowpea infection by *A. vogelii* when pre-emergence herbicide mixtures containing pre-emergent (metazachlor + antidote) are applied followed by post-emergence application of imazaquin at 0.18 kg a.i/ha<sup>-1</sup> [25]. This method could be used to control *A. vogelii* in BGN.

### 14. Soil Fertility Amendments

Nitrogen and phosphorus deficiency as well as water stress accentuate the severity of *A. vogelii* damage to the hosts [46]. The deficiency of these nutrients is active at stimulating germination of root parasitic plant seeds and the increase is

due to an increase in the production of SLs [53]. Parasitic weeds are most challenging on soils with low fertility, especially soils with low phosphorus and nitrogen [55]. This has a significant impact on plant growth and health. There is a need to use fertilizers to improve soil fertility and plant health to withstand infection from parasitic weeds [53].

According to Rambakudzibga [55] phosphorus (P) suppresses *A. vogelii* development and therefore its yield thus limiting its effects on cowpea. On the contrary, *S. generioides* infection does not seem to be influenced by nitrogen [57]. Application of a nitrogen fertilizer on a cowpea crop is, however, highly unlikely. In Zimbabwe, BGN is treated like cowpeas as an underutilized crop grown as a low-input crop with no fertilizer application [55].

The impact of nitrogen (N) application on the rate and yield decline impacts of parasitic weeds has been studied. The amount of cowpea infected and *A. vogelii* totals were reliably reduced by 60 kg·ha<sup>-1</sup> N, however, this rate significantly discouraged cowpea grain yield compared to 0 and 30 kg·ha<sup>-1</sup> N [58]. The interaction of cowpea varieties and mixtures of nitrogen and phosphorus, versus delayed *A. vogelii* emergence, was likewise reported [55]. Phosphorus also reduced *A. vogelii* growth by increasing the mineral content of the host plant to the toxicity level; hence the reduction in the injury caused by the parasite on the crop [59] and increased cowpea grain yield. On the other hand, *S. generioides* infection does not seem to be affected by nitrogen [57].

Research down in Bostwana demonstrated that neither single superphosphate nor ammonium nitrate at prescribed levels for cowpea influenced the invasion level of *A. vogelii* on cowpea when applied as a residual treatment [17]. Kabambe and Bokosi [60] also reported increment in cowpea grain yield due to the application of P under *A. vogelii* infestation. It has been reported that P reduces the production of SLs at the root level, which are required for stimulating parasitic weed seeds [40]. There is a possibility that the addition of P could reduce the *A. vogelii* attachments through this process.

Akande *et al.* [61] reported that complementary use of Ogun rock phosphate and cow dung increased yield of cowpea in Nigeria. Karanja *et al.* [62] reported that cattle manure at 5 t·ha<sup>-1</sup> suppressed *A. vogelii* and improved yield of cowpea but effects depended on cowpea variety. According to Kabambe *et al.* [60], the use of cattle manure at 5 t·ha<sup>-1</sup> had direct suppressive effects on *A. vogelii* emergence, with small and inconsistent yield benefits. The use of fertilizers may be a useful method of reducing SLs production by the host plants and henceforth, reducing parasitic weed infection. The response in strigolactone production or exudation to nutrient availability differs between plant species therefore it is important to note this before using fertilizers [53]. The combined suppression of *A. vogelii* through fertilizer and genotype resistance could form a strong base for reducing *A. vogelii* seed bank in the soil.

## 15. Host Plant Resistance

One of the promising strategies for limiting damage by parasitic weeds is the use

of crop varieties with improved levels of resistance and tolerance against parasite. Resistant genotypes have less infections, whereas tolerant genotypes display less injury of growth or losses in grain when exposed to similar levels of infection than other varieties of the same species [17]. The types of resistance occurring in parasitic plant hosts are classified into reduced host strigolactone production, reduced haustorium initiation imitation factor production, host resistance to parasite establishment and host resistance after parasite establishment [50].

The use of host plant resistance in *A. vogelii* controlling is now a promising strategy for parasitic weeds, which is practical and environmentally friendly [63]. Significant progress has been made in developing screening methodologies for the identification of better sources of parasitic weed-host resistance [46]. The resistance of BGN cultivars that produce little or no strigolactone stimulants, can be used under different environmental conditions, which include unreliable or erratic rainfall, low soil fertility and primitive agriculture. There are other factors involved in the resistance mechanism such as avoidance due to precocity known in some legumes, early flowering, earlier pod setting and maturity, which would restrict the dry-matter partitioning into parasites [63]. Legume crops are capable of biological nitrogen fixation, therefore tolerant or resistance genotypes exhibit high growth and high nodulation under the influence of *A. vogelii* [63] [64]. It has been reported that susceptible legumes cultivar for example soya bean, have non-viable nodules due to *A. vogelii* infestation as it interferes with rhizobium nodulation given their high photosynthetic capacity [63].

In Zimbabwe, two pre-released cowpea varieties C/83/4/6 and C/85/6/4 were found to be moderately susceptible because they were able to produce grain and still needed further evaluation under field conditions [65]. Kabambe *et al.* [22] recommended the use of resistant soy-bean types Bossier and Ocepara-4 on *A. vogelii* infested fields and utilize pigeon peas or green manure as trap crops for *S. asiatica*, to while avoid damage or building of *A. vogelii* on their farms. These crops can also be used as an integrated management approach in the management of both parasitic weeds.

In Malawi line IT99K-7-21-2-2-1 was selected as the best in terms of *A. vogelii* resistance, yield and grain size by farmers. On the basis of *A. vogelii* resistance and earliness, cowpea lines IT99K-7-21-2-2-1, IT99K-573-1, TZA 263 and Mkanakafiti were selected as best genotypes [60]. In West Africa, cowpea breeding for resistance to *S. gesnerioides* was found using Botswana landrace B301 as a source of resistance. Landrace B301 is resistant to both *S. gesnerioides* and *A. vogelii*, with resistance to each weed being conferred by independent non-allelic genes [18]. In addition, in West Africa, different dominant genes for resistance have been identified. These lines have been used as complimentary parents when breeding for all cultivars [52]. Resistance to *A. vogelii* was discovered after screening more than 650 cowpea accessions. Mkanakafiti and IT99K-7-21-2-2-2XIT82E-16 are suitable cowpea varieties for production in Malawi as the inoculum in the soil banks would decrease, hence decrease the level of infestations on other suit-

able hosts as revealed by the studies done by [18]. Mkanakaufiti (21.9 g/pot) showed higher yield followed by IT82E-16 (12.5/pot) which was susceptible but with tolerance ability to the parasitic weed [18]. The study showed that resistance mechanisms can be categorized as no or few *A. vogelii* shoots, death of *A. vogelii* shoots and late infestation.

On the other hand, field research done by Kabambe *et al.* [60] revealed that Mkanakaufiti variety even though it did demonstrate resistance to *A. vogelii*, it had a low yield. This was in agreement with Karanja *et al.* [21] also showed that resistant germplasm to *A. vogelii* did not always give high yields, but provided source of germplasm for improvement. Kabambe *et al.* [60] also stated that lack of variety x fertilizer interaction on grain yield in all site-years revealed that IT82E-16 of being a well-adapted and high yielding, variety, but was not responsive to fertility amendments. Henceforth breeding activities are mandatory to improve genotypes that can respond to fertility improvements.

## 16. Low Germination Stimulant Production

According to Jamil *et al.* [66], the opportunity to minimize the chance to reduce losses through avoiding triggering escaping causes of *Striga* seed germination through reduced strigolactone production exists. Low germination stimulation production which has been exploited as a positive mechanism of resistance in breeding sorghum cultivars that are resistant to *Striga asisatica* Ejeta *et al.* [67], was considered as not significant in Scrophulariaceae especially in legumes [68]. Low germination stimulant (Lgs) trait is inherited as a single, nuclear, recessive gene with largely additive gene action [69]. According to Ejeta *et al.* [70], the Lgs gene found in a source germplasm has been transferred were transferred into high yielding and broadly adapted sorghum cultivars. Sorghum cultivars with this mechanism are Framida, SRN 39, 555, SAR lines, IS 15401 and IS 9830 [71]; [69]. Lgs have been found in some legume and sunflower accessions that showed improved resistance to *Orabanche* species [72]. BGN genotypes with this mechanism still need to be investigated through germplasm screening.

## 17. Hypersensitive Response

Hypersensitive response is another mechanism of resistance that causes failure of haustorial formation at the potential host. *A. vogelii* seeds germinate as usual and the radicles attached to the roots but the resistant roots do not permit haustorium development [63]. For instance, cowpea cultivar B301 is resistant to races SG3 and SG4 of the root parasitic weed *S. gesnerioides*, developing a hypersensitive response at the site of parasite attachment [69]. Cowpea genotypes with this resistant mechanism show necrotic lesions on the host cell around the point of infection, but most remain more localized to the site of *A. vogelii* invasion. This discourages further advancement of attached *A. vogelii* which does not develop normally and eventually dies on the host within 3-4 days [26] [69]. Death of host cells results in unsuccessful establishment of the parasite, hence its ultimate de-

mise. This mechanism of resistance is described as analogous to the hypersensitive response shown in plant-pathogen interaction. Hypersensitive reaction is conditioned by two complementary dominant genes [26].

## 18. Parasite Establishment Resistance

In some cultivars, parasite seedlings penetrate the host root cortex but are unable to form vascular continuity with the host and dies [26] [46]. The tubercles start to develop on the host root surface but do not enlarge, remaining less than 0.5 mm in diameter or fails to expand their cotyledons and eventually the parasite fails to establish neither vascular bundle nor develop internal organization [16] [73]. Vascular continuity allows movement of water and nutrients from host to parasite.

## 19. Transplanting and Deep Sowing

Transplanting seedlings rather than direct sowing of seed reduces infestation by parasitic weeds. It offers the crop a time advantage and thereby renders it more aggressive with parasitic weeds such as *Striga* and *A. vogelii* [52]. Transplanting is often used in lowland rice production as a general means to escape from weed competition Rodenburg and Johnson [74], and to facilitate weeding operations (in row-planted crops). For these reasons, transplanting was recommended as an excellent practice in lowland rice fields infested with the *Rhampicarpa fistulosa* [27]. Transplanting has also been demonstrated as an effective way to reduce *Striga* infestations in sorghum, in comparison to seed-sown [74].

Deep ploughing is a method that can be used in controlling the level of *A. vogelii* infection on BGN. It enables the weed seeds to be brought to a greater depth within the soil profile where they cannot germinate due to shortage of oxygen which is a factor required for *A. vogelii* seeds to germinate. Rubiales and Fernandez-Aparicio [52] reported that *A. vogelii* is sensitive to oxygen deficiency which limits its spread to soils with permeability and drainage. At greater depth, there are high carbon dioxide levels and this enhances carbon dioxide narcosis which results in the rotting of the *A. vogelii* seeds thereby reducing the number of seeds in the seed bank.

When deep planting was combined with no-tillage, *Striga* seed production was completely suppressed. Practices like these require, however, extra labor (for example transplanting compared to direct sowing, digging planting holes compared to conventional sowing practices) and still have clean trade-offs with other management operations such as land preparation and mechanical weeding.

Cultivation of the soil can intensely affect the parasitic weed seed bank. Minimum tillage can add to parasitic weed control by decreasing the amount of viable seeds merged into the soil [52]. No tillage has been reported to significantly reduce *O. crenata* infection on faba bean [52].

## 20. Sowing Date

Early planting of legumes causes a severe attack on parasitic weeds. According to

Pérez-de-Luque *et al.* [75], stated that early sowing resulted in high crop losses due to a higher infection level and longer exposure to parasite attack. For example, chickpea that was sown in October had an initial vegetative growth when temperatures were still moderate, and thus, developed more roots that were prone to infection early [76]. On the other hand, susceptible cultivars were more severely affected by the parasite with early sowing due to late maturity [76]. It is important to use resistant cultivars to prevent parasitic weeds as a control strategy. According Pérez-de-Luque *et al.* [75] for resistant cultivars, allow for early planting as well as having a longer period to maturity with little parasitic weeds attachment or shoot emergence, which results in a higher yield.

Delay in sowing is said to have a strong effect on parasitic weeds attack in legume, especial on *Orobanche crenata* [75]. According to Pérez-de-Luque *et al.* [75], delayed sowing on *O. crenata* emergence was strongly influenced by the crop, the cultivar, and the environmental conditions during the season. Due to delayed sowing time, there is reduced parasitic emergence on susceptible genotypes [75]. According to Rubiales *et al.* [72], delayed sowing reduced *Orobanche crenata* infection in low temperatures like winter. Due to the effects of lower temperatures, *Orobanche* seeds are induced into secondary dormancy [72]. This could be the same *A. vogelii* once planted late in the BGN infected field.

## 21. Hand Weeding/Hand Pulling

The most common control method used against *A. vogelii* is hand weeding and pulling. It is recommended to prevent seed set and seed dispersal [46]. The hand weeding method is mainly accomplished after parasitic damage has already been done to the host plant. It is not practical to hand pull *A. vogelii* weeds on dense infestations due to high labour cost in repeated pulling. The method is only practical at a low level of infestation before the parasitic weed flowers. However, combined with other methods to control the parasitic weeds, it can reduce the seed bank very efficiently [77].

## 22. Arbuscular Mycorrhiza Fungi

Arbuscular mycorrhiza fungi (AMF) have the potential to control parasitic weeds. These fungi live in terrestrial ecosystems and associate with common land plants forming the most widespread types of symbiosis on earth [78]. AMF is obligate biotrophs and rely on strigolactone from their host to engage in their developmental cycle and colonize a plant root. AMF supply their host with water and minerals especially inorganic phosphate (Pi), and offer a certain degree of protection against pathogens [79]. In return the AMF, receive carbohydrates from their host. The presence of AMF hyphal networks and the better mineral nutrient availability in the natural ecosystem keep strigolactone exudation by host plants within limits that do not induce a lot of parasitic seeds to germinate and infect their host [53]. In addition, to the effect impact of AMF interaction on SLs creation, this advantageous interaction gives protection from biotic stresses

to the host plant by inducing defense-related genes [53]. This is why, after arbuscular mycorrhiza (AM) symbiosis interaction, plants are infected to a lesser degree by *Striga spp.* There are three positive effects of AM colonization to plants that is facilitating the uptake of mineral nutrients by plants, their effect in reducing strigolactone production and on the induction of plant defense genes make AMF a suitable and promising tool for controlling parasitic weeds [53]. Studies show that the Orobanchaceae/host interaction was influenced by the protective effect of AMF against various pathogens. Research by Lenzemo and Kuyper [80], showed that mycorrhizal inoculation could mitigate the harm caused on sorghum by *Striga hermonthica*. It also reduced the level of host infestation in some cases, Louarn *et al.* [81] by reducing the release of germination stimulants or SLs by mycorrhizal plants. Mycorrhizal colonization of pea plants also showed the reduction of production of Orobanche and Phelipanche seed germination SLs [47]. Lopez-Raez *et al.* [53] demonstrated in tomatoes that biochemically root colonization by AMF reduced the synthesis and exudation of SLs.

### 23. Integrated Weed Management

To date, no single approach has led to a long-term solution to control parasitic weeds [53]. For effective control, durable and economic, measures need to be combined [82]; [54]. The challenge is to integrate practices that obtain optimum efficiency in terms of reduction of existing seed banks, prevention of seed production and avoidance of seed dissemination, with input rates affordable to individual and often resource-poor farmers [83]. Combined use of hand weeding/pulling, fertilizer application, trap crops, catch crops and use of resistant varieties have been recommended to reduce *A. vogelii* or *Striga* damage [24] [54]. Hand pulling of emerging *A. vogelii* can be done only after appearance of the weeds above the ground. It is an important measure to reduce future infestation if done prior to seed production and release [24]. Trap crops and catch crops may reduce to some extent the *A. vogelii* seed germination without being parasitized contributing to seed bank depletion. AMF has been reported to control *Striga* and *A. vogelii* and enhance biomass production of compatible hosts when integrated with resistance genes [24] [54]. According to research the integration of multiple control strategies is suggested as a better approach to deal with parasitic weed [46] [54]. Combined use of row planting, fertilizer, and hand pulling flowering recorded 48% higher grain yield and over 50% reduction in *Striga* shoot counts [46]. The results showed that the optimum solution in the control of *Striga*, was by integrated approach that were affordable and acceptable by farmers [24] [46].

### 24. Conclusion

BGN is an under-utilized legume crop and grows as landrace varieties with unpredictable productivity. The crop is tolerant to drought, adapts to severe envi-

ronments and has the ability to produce some yield where other legumes may not grow well and where pest and disease control do not seem to be given serious attention giving it a climate smart crop status. Yields of BGN in the southern Sahara of Africa are low because of biotic factors which incorporate *A. vogelii* and *S. gesnerioides*. A few social and compound control measures are accessible to control *A. vogelii*. These procedures are frequently inadequately received by smallholder farmers. Based on the review findings, various control mechanisms for dealing with the harmful effects of *A. vogelii* have been proposed. Different control methods are cultural and mechanical management procedures, phosphorus fertilizers and resistant host crops, herbicide use, and integrated *A. vogelii* control methods. In adaptive methods, however, new techniques remain important. The life cycle for root parasitic weeds is inextricably linked to that of their host, making it an ideal target for such new control techniques, especially when aimed at the early stages of the host-parasite relationship. The methods reveal additional information on the function of parasitic seed germination strigolactones and how they can be used in breeding for management of parasitic weeds. The implementing AMF-friendly social practices, such as reducing culturing and fungicide application, could boost growth and increase dry season resistance in trim, potentially reducing *A. vogelii* invasions.

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### Conflicts of Interest

Authors declare no conflict of interest.

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