



## **Enhancement of the Productivity of Soybean in Malawi through Foliar Application of Nutrients**

**Austin T. Phiri<sup>1\*</sup>, Pacsu Simwaka<sup>1</sup> and Daniel Kausiwa<sup>1</sup>**

<sup>1</sup>*Department of Agricultural Research Services, Bvumbwe Agricultural Research Station, P.O. Box 5748, Limbe, Malawi.*

### **Authors' contributions**

*The work was conducted in collaboration among all authors. Author ATP designed the study. Authors PS and DK managed the experiments and collected data. Author DK performed laboratory analysis of soil samples. Author ATP performed the statistical analysis and managed the literature searches. All authors read and approved the final manuscript.*

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### **ABSTRACT**

In Malawi, inoculating soybean with rhizobia, has been advocated for decades as a way of boosting productivity through enhancement of biological nitrogen fixation. The effectiveness of this strategy however, has been constrained by the low soil fertility status of soils in Malawi, necessitating the use of mineral fertilizer to supply nutrients to the soybean for increased productivity. Alternative strategies like foliar feeding of nutrients to improve grain yields are yet to be widely promoted due to lack of research evidence. Therefore experiments involving the soybean were conducted during the 2016/17 cropping season, laid in a randomized complete block design (RCBD) replicated four times, at Bvumbwe, Bembeke and Chitala in Malawi to evaluate yields response to foliar feeding using a foliar fertilizer (Allwin-legumes). Agronomic data were analyzed in Genstat Discovery Edition 4 and were subjected to analysis of variance at 95% level of confidence. Means were separated using the least significant difference ( $LSD_{0.05}$ ). Generally, the result indicate that foliar feeding produced significantly higher ( $p < 0.05$ ) grain yields ranging from 33.7-364.7%, above the control across the different agro-ecological zones. The result underscores the importance of judicious and methodical application of nutrients to soybean under the changing climate and conditions of low soil fertility. In

\*Corresponding author: E-mail: [phiriaustin534@gmail.com](mailto:phiriaustin534@gmail.com);

general, foliar feeding using Allwin fertilizer particularly when conducted twice can increase significantly soybean productivity in Malawi. The grain yields increase is attributable to the enhanced crop growth and development through foliar supply of nutrients.

**Keywords:** Soybean; inoculation; foliar fertilizer; productivity; soil; climate.

## 1. INTRODUCTION

In Malawi, soybean (*Glycine max*), a legume, is particularly important not only for the potential for soil fertility improvement, but also for addressing human nutritional deficiencies through traditional diets [1]. Regionally, Malawi is the third largest producer of soybean in the Southern Africa Development Community (SADC) after South Africa, and Zambia, though having more land under the crop than Zambia [2]. Presently, the mean grain yield for soybean under smallholder farmers' conditions is pegged at 892 kg ha<sup>-1</sup> against a yield potential of about 4,500 kg ha<sup>-1</sup> for most varieties currently being cultivated in the country [3]. An array of production constraints, have kept the productivity of the crop far below the yield potential of the varieties currently being grown. The low productivity has chiefly been attributed to low fertility status of soils in Malawi, which are inherently low in nitrogen (N), phosphorus (P) [4] and Sulphur (S) [5]. In recent years, climate change also has had a profound negative effect on the productivity of the crop [6]. It is worthwhile to note that legumes, fix atmospheric N through a symbiotic relationship with nodule dwelling *rhizobium* bacteria, through a process called Biological Nitrogen Fixation (BNF) [7]. N, P and S are requisite in the growth and development of the legumes. Root development and subsequent nodule formation after root infection by the N fixing bacteria requires energy derived from phosphorus containing molecule called Adenosine triphosphate (ATP) [8]. Furthermore, nitrogen is required for the general vegetative growth of the legumes. The element is part of leaf protein that is vital for chloroplast formation and photosynthesis [9]. It follows therefore that where the element is limiting photosynthesis is crippled hence crop development and productivity is reduced. This is most critical in the early stages of the development of leguminous crops before N fixation by the nodule dwelling bacteria commences. It is worthwhile to note that only 25% to 60% of N in most legumes' dry matter is derived from symbiotic N fixation, the rest is absorbed from the soil [10]. Sulfur is an essential element for growth and physiological functioning of plants [11]. However, some evidence suggest

that growth of some nodule dwelling N fixing *Bradyrhizobia* strains in legumes is limited by S deficiency [12].

Legumes have a high demand for iron (Fe) [13]. The element is required for the synthesis of Fe-containing proteins, leghemoglobin plus nitrogenase and cytochromes of the electron transport chain in bacteroids [13]. Fe deficiencies can affect nodule initiation and development [13]. Deficiencies of Fe in the soil are not common in Malawi. Over 40% of soils in Malawi are Oxisols and Ultisols, which are highly weathered [14]. Intense weathering and leaching in these soils increased the loss of base cations and silica, producing residual build-up of Fe and Al oxides overtime [13], hence the high Fe content.

Potentially, nutrient deficiencies in some soils that reduce legume productivity can be addressed through foliar feeding by using foliar fertilizer. A study therefore was conducted to: i) evaluate the effects of foliar feeding on nodule development and effectiveness for soybean ii) and evaluate the effects of foliar feeding on soybean grain yields.

## 2. MATERIALS AND METHODS

### 2.1 Materials

Soybean seed (Tikolore; yield potential of 2.5-3.0 t ha<sup>-1</sup>), Nitrofix (soybean inoculant), Allwin foliar fertilizer (Legumes) and knap sack sprayers.

### 2.2 Laboratory and Data Analysis

Baseline composite soil samples for each site sampled randomly at 0-20 cm and 20-40 cm were collected before the establishment of the experiments. Laboratory soil analysis was done in order to characterize the soil. The soil samples were analyzed for OC, total N, available P, K, Mg, Ca and soil pH (H<sub>2</sub>O). Soil pH was quantified in water (1:2.5) using pH meter [15]. Soil analysis for P, K, Mg and Ca was done by Mehlich 3 extraction procedures [16] while OC was determined using the colorimetric method [17] and total N was determined by Kjeldahl method [18]. Molybdenum (Mo) was analyzed using the

hand held XRF machine [19]. Biomass yields for the legumes were assessed as described by [20]. All the agronomic data were analyzed using Genstat statistical package and were subjected to analysis of variance at 95% level of confidence. Means were separated by the least significant difference ( $P < 0.05$ ).

### 2.3 Soil Physical and Chemical Characteristics at the Study Sites

Tables 1-3 shows the soil physical and chemical characteristics at the study sites. In general, the laboratory analytical data indicate that the soil at Bvumbwe had texture that was predominantly sandy loam (SL). Soil pH was moderately acid (5.6-6.0) between 0-20 cm to 20-40 cm; OC was low (<0.88%) while total N was very low (<0.08%) between 0-20 cm to 20-40 cm. Available P was very high ( $> 34 \text{ mg kg}^{-1}$ ) between 0-20 cm to high ( $25-33 \text{ mg kg}^{-1}$ ) between 20-30 cm; K was low ( $0.06-0.10 \text{ cmol kg}^{-1}$ ) at the sampled depths; Ca was adequate ( $> 2 \text{ cmol kg}^{-1}$ ) while Mg was low ( $< 3.0 \text{ cmol kg}^{-1}$ ). Zinc was very low ( $< 1.0 \text{ mg kg}^{-1}$ ) while Cu was low ( $< 0.3 \text{ mg kg}^{-1}$ ).

At Chitala the soil texture was predominantly sandy clay loam (SCL); soil  $\text{pH}_{\text{H}_2\text{O}}$  was acid (5.1-5.5) both between 0-20 cm and 20-40 cm; OC content was within the medium range (0.88-

2.35%); total N content was high (0.20-0.30%) between 0-20 cm and low (0.08-0.12%) between 20-40 cm. Available P was very low ( $< 8.0 \text{ mg kg}^{-1}$ ); K was low ( $0.06-0.10 \text{ cmol kg}^{-1}$ ) between 0-20 cm but adequate ( $0.11-0.40 \text{ cmol kg}^{-1}$ ) between 20-40 cm; Ca was adequate ( $> 2 \text{ cmol kg}^{-1}$ ), Mg was low ( $< 3.0 \text{ cmol kg}^{-1}$ ) while Zinc was very low ( $< 1.0 \text{ mg kg}^{-1}$ ).

At Bembeke, soil texture was predominantly sandy clay loam (SCL). Soil  $\text{pH}_{\text{H}_2\text{O}}$  was very strongly acid ( $< 4.5$ ) both between 0-20 cm and 20-40 cm. OC was within the medium range (0.88-2.35%) between 0-20 cm and 20-40 cm. Total N content was low (0.08-0.12%) at both; Available P was very low ( $< 8.0 \text{ mg kg}^{-1}$ ) between (0-20 cm) and low ( $9-18 \text{ mg kg}^{-1}$ ) between 20-40 cm. K was very low ( $< 0.05 \text{ cmol kg}^{-1}$ ) at both levels across the field. Ca was adequate ( $> 2 \text{ cmol kg}^{-1}$ ), Mg was low ( $< 3.0 \text{ cmol kg}^{-1}$ ) while Zinc was very low ( $< 1.0 \text{ mg kg}^{-1}$ ).

### 2.4 Rainfall Characteristics of the Study Sites

The study sites received adequate rainfall (Fig. 1-3) during the 2016/2017 cropping season with the highest amount recorded in Bvumbwe (3,108.8 mm), followed by Bembeke (1,186 mm), and Chitala (868.3 mm).

Rainfall at Bvumbwe during the 2016/17 cropping season

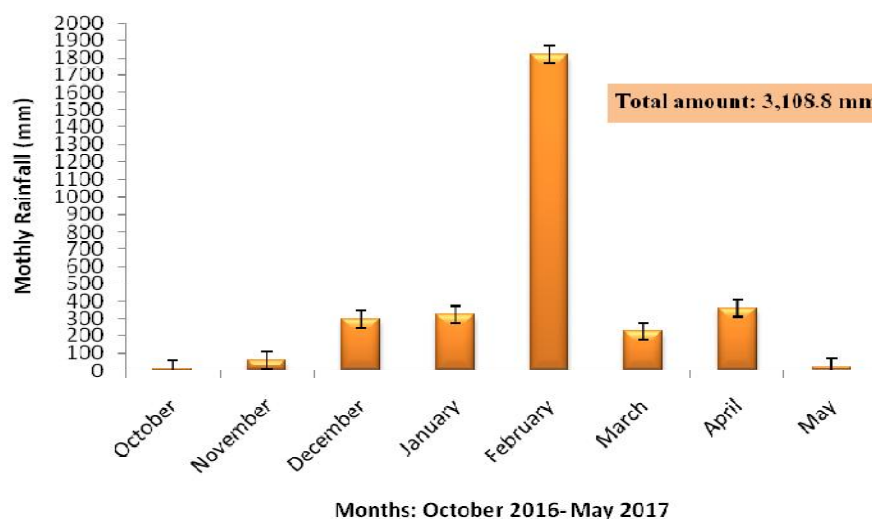
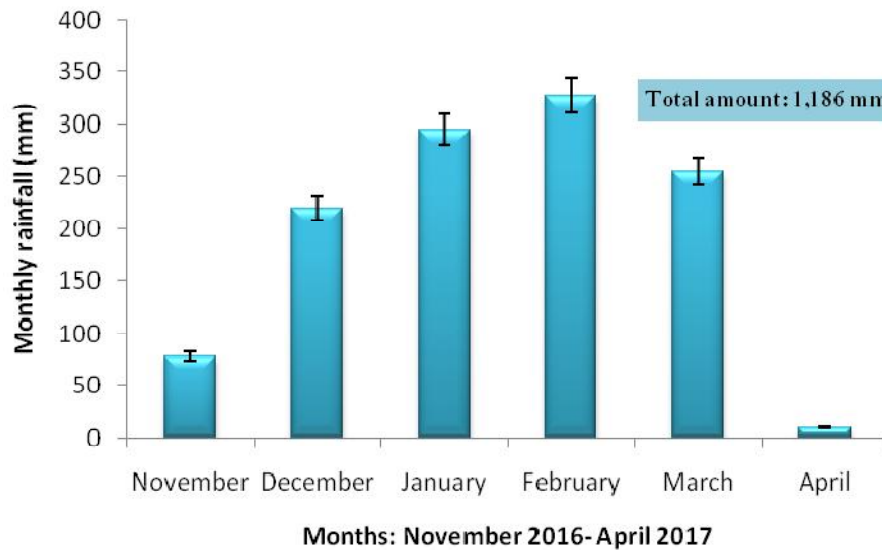


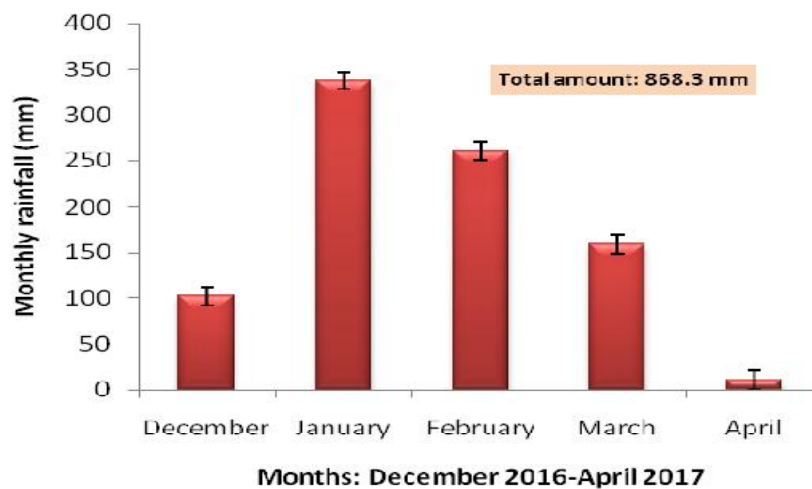
Fig. 1. Rainfall at Bvumbwe during the 2016/17 cropping season

**Rainfall at Bembeke during the 2016/17 cropping season**



**Fig. 2. Rainfall at Bembeke during the 2016/17 cropping season**

**Rainfall at Chitala during the 2016/17 cropping season**



**Fig. 3. Rainfall at Chitala during the 2016/17 cropping season**

**2.5 Methods**

The experiments were laid out in a randomized complete block design (RCBD) with eight treatments replicated four times. Plot size was 5m x 5m for each treatment. The experiments were conducted on station at Bvumbwe and Chitala agricultural research stations and Bembeke sub-agricultural research station during the 2016/2017 cropping season.

**2.6 Treatments**

The treatments were as follows. 1. Control (soybean only), 2. Inoculated soybean, 3. None inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence, 4. None inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence, 5. None inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence, 6.

**Table 1. The soils' physical and chemical properties before the experiment at Bvumbwe agricultural research station**

Depth (cm)	Silt %	Clay %	Class	pH	O C %	N %	P mg kg <sup>-1</sup>	K cmol kg <sup>-1</sup>	Ca cmol kg <sup>-1</sup>	Mg cmol kg <sup>-1</sup>	Zn mg kg <sup>-1</sup>	Cu mg kg <sup>-1</sup>	Mo mg kg <sup>-1</sup>
0-20	10	37	SC	5.7	0.76	0.07	42.1	0.08	4.3	0.21	0.12	0.08	71.5
20-40	10	37	SC	5.6	0.86	0.07	30.5	0.08	4.4	0.25	0.20	0.23	76.0

**Table 2. The soils' physical and chemical properties before the experiment at Chitala agricultural research station**

Depth(cm)	Silt %	Clay%	Class	pH	O C%	N%	P mg kg <sup>-1</sup>	K cmol kg <sup>-1</sup>	Ca cmol kg <sup>-1</sup>	Mg cmol kg <sup>-1</sup>	Zn mg kg <sup>-1</sup>	Mo mg kg <sup>-1</sup>
0-20	8	25	SCL	5.4	2.3	0.20	6.49	0.10	7.78	0.39	0.03	5.5
20-40	6	25	SCL	5.5	0.93	0.08	2.09	0.11	8.07	0.41	0.36	10.0

**Table 3. The soils' physical and chemical properties before the experiment at Bembeke sub-agricultural research station**

Depth(cm)	Silt %	Clay %	Class	pH	O C %	N %	P mg kg <sup>-1</sup>	K cmol kg <sup>-1</sup>	Ca cmol kg <sup>-1</sup>	Mg cmol kg <sup>-1</sup>	Zn mg kg <sup>-1</sup>	Mo mg kg <sup>-1</sup>
0-20	15	29	SCL	4.18	1.41	0.11	7.5	0.04	3.9	0.41	0.19	3.0
20-40	14	33	SCL	4.23	1.29	0.12	18.9	0.04	2.1	0.17	0.10	3.5

Inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence, 7. Inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence, 8. Inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence. Spraying Allwin (3 gm/l) once at two weeks from emergence translated to applying 0.3 kg N ha<sup>-1</sup>, 0.04 kg P ha<sup>-1</sup>, 0.04 kg Fe ha<sup>-1</sup> and 0.07 kg S ha<sup>-1</sup>; while spraying Allwin (3gm/l) once at four weeks from emergence translated to applying 0.5 kg N ha<sup>-1</sup>, 0.08 kg P ha<sup>-1</sup>, 0.06 kg Fe ha<sup>-1</sup> and 0.13 kg S ha<sup>-1</sup> and spraying Allwin (3 gm/l) twice at two and four weeks from emergence translated to applying 0.8 kg N ha<sup>-1</sup>, 0.12 kg P ha<sup>-1</sup>, 0.10 kg Fe ha<sup>-1</sup> and 0.20 kg S ha<sup>-1</sup>.

## 2.7 Height Measurement

Height measurements were conducted on samples collected before the first application of Allwin foliar fertilizer and samples collected at two weeks after the second application of Allwin and at harvest. Vertical growth rate was calculated by dividing the measured height with the number of days from seedling emergence [21,22].

## 2.8 Nodulation Study for Soybean

The plants were carefully uprooted at four and six weeks after emergence. The soil was removed by gentle shaking. Counting and weighing of nodules was conducted from three plants per treatment plot and recording of the data was done. All the nodules per sampled plant were studied for effectiveness. The nodules were cut open and nodule contents described as red (including pink) indicating effective nodulation or other (white, green or grey) indicating none effective nodulation.

## 2.9 Biomass and Grain Yields Assessment

Grain yields assessment was conducted at physiological maturity of the legumes between June and July, 2017. Pods were harvested from a 2 m x 2 ridges net plot. The pods were shelled and weighing of the grains and the husks/shells was done. These were later oven dried for 24 hours at 70°C to constant weights. Estimation of the mean number of pods per plant was done by counting the total number pods from five plants in the net plot and dividing by five to get the mean.

## 3. RESULTS

### 3.1 Soybean Growth Rate

#### 3.1.1 Soybean growth rate at Bvumbwe agricultural research station

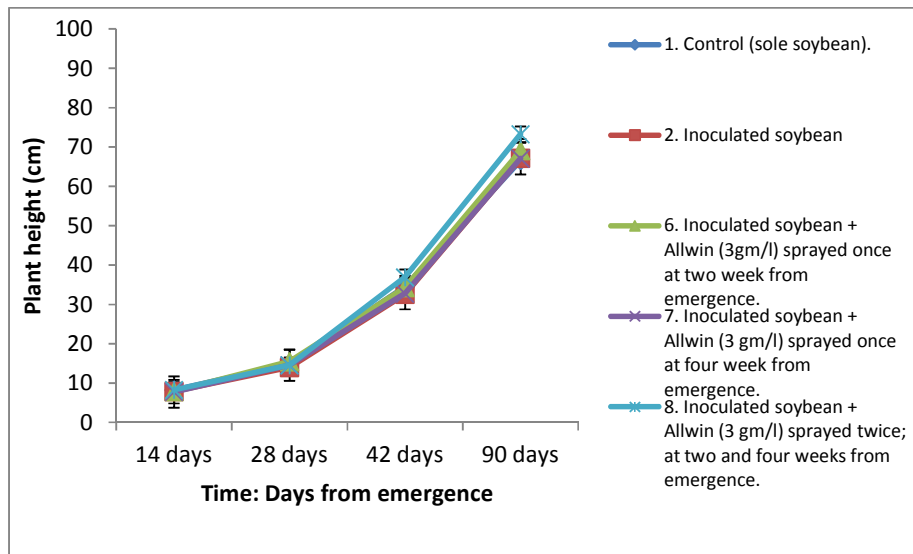
Fig. 4 Shows the effect of combining soybean inoculation with the foliar application of Allwin fertilizer (legumes) on soybean growth rate at Bvumbwe Agricultural Research Station. Combining soybean inoculation and foliar application of Allwin fertilizer (legumes) twice, at two and four weeks from emergence seemed to have thinly accelerated soybean growth rate compared with the other treatments.

Fig. 5 shows the effect of foliar application of Allwin fertilizer (legumes) on soybean growth rate. Foliar application of the fertilizer either once at two or four weeks from emergence and twice, at two and four weeks from emergence seemed not to have accelerated soybean growth rate compared with the control, though at about sixty days from emergence, beyond, the former treatments appeared to have slightly accentuated growth rates above the control.

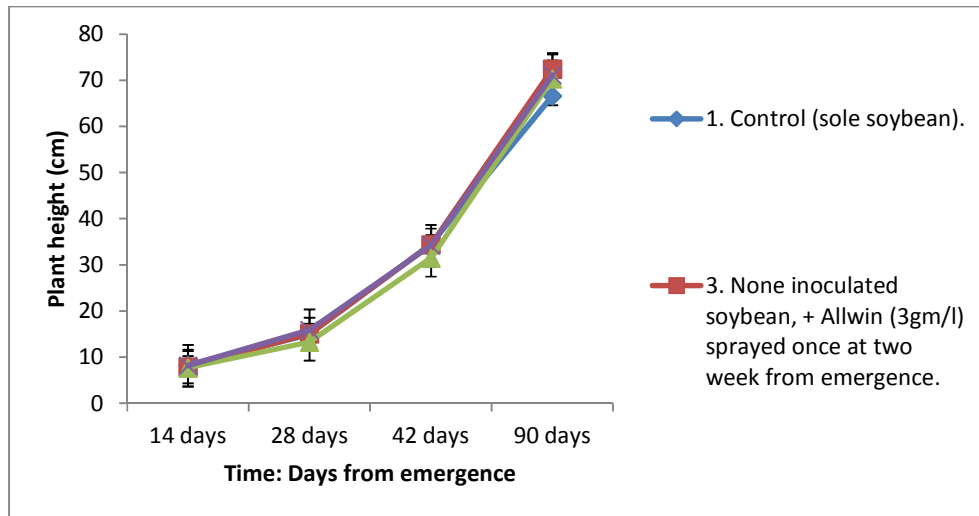
#### 3.1.2 Soybean growth rate at Bembeke sub-agricultural research station

Fig. 6 shows the effect of combining soybean inoculation with the foliar application of Allwin fertilizer (legumes) on soybean growth rate at Bembeke sub-Agricultural Research Station. Combining soybean inoculation and foliar application of Allwin fertilizer (legumes) once at two and four weeks from emergence and twice, at two and four weeks from emergence, seemed to have accelerated soybean growth rate compared with the control. Noticeably, at about forty two days from emergence, apart from treatment six (inoculating soybean and foliar application of Allwin fertilizer once at two weeks from emergence), growth rate in the treated plots apparently decreased but remained steady in the control treatment.

Fig. 7 shows the effect offoliar application of Allwin fertilizer (legumes) on soybean growth rate. Foliar application of Allwin fertilizer (legumes) either once at two or four weeks from emergence and twice, at two and four weeks from emergence seemed to have increased soybean growth rate compared with the control. Treatment three (application of Allwin foliar



**Fig. 4. The effect of combining soybean inoculation with the foliar application of Allwin fertilizer (legumes) on soybean growth rate**



**Fig. 5. The effect of sole foliar application of Allwin fertilizer (legumes) on soybean growth rate**

fertilizer at two weeks from emergence without inoculating the soybean) had a more accentuated growth rate above other treatments. Visibly, in the control plot, growth rate seemed to have increased towards the maturity stage of the crop.

### 3.1.3 Soybean growth rate at Chitala agricultural research station

Fig. 8 shows the effect of combining soybean inoculation with the foliar application of Allwin fertilizer (legumes) on soybean growth rate at

Chitala Agricultural Research Station. Combining soybean inoculation and foliar application of Allwin fertilizer (legumes) once at two weeks from emergence and twice, at two and four weeks from emergence seemed not to have accelerated soybean growth rate compared with the control. Notably though, between the twenty eighth and at about day forty two from emergence, growth rate in the control and treatment seven (inoculating soybean and foliar application of Allwin fertilizer once at four weeks from emergence), appeared to have accelerated but remained steady in the other treatments.

After forty two days from emergence growth rate in the control treatment seemed to have decrease but was constant in the seventh treatment.

foliar application of Allwin fertilizer either once at two or four weeks from emergence or twice, at two and four weeks from emergence, seemed to have not accelerated growth rate above the control. Notably, growth rate was slow in treatment four below the control. However, a brief increased soybean growth rate in the control treatment above treatment three and five

Fig. 9 shows the effect of foliar application of Allwin fertilizer on soybean growth rate. A close observation of the growth pattern indicate that

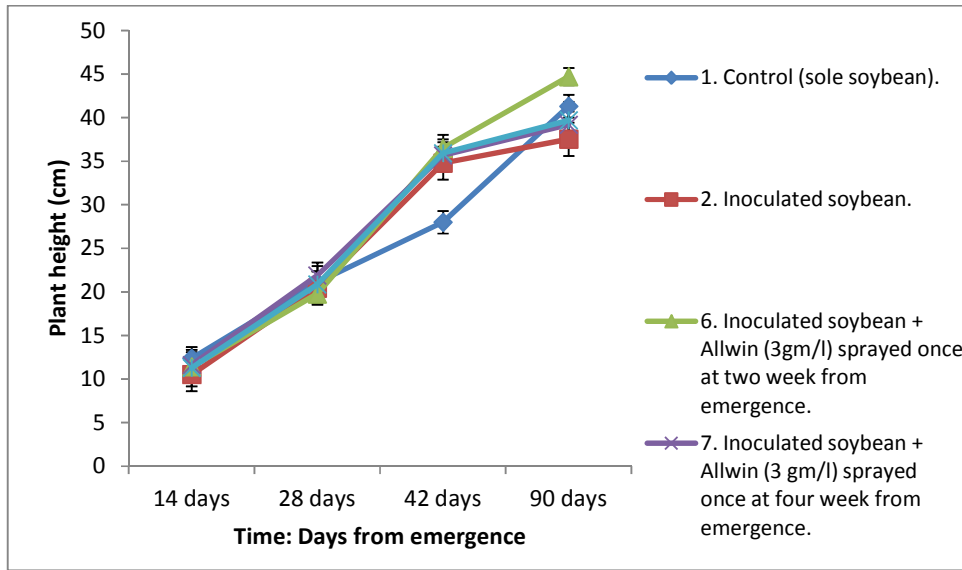


Fig. 6. The effect of combining soybean inoculation with the foliar application of Allwin fertilizer (legumes) on soybean growth rate

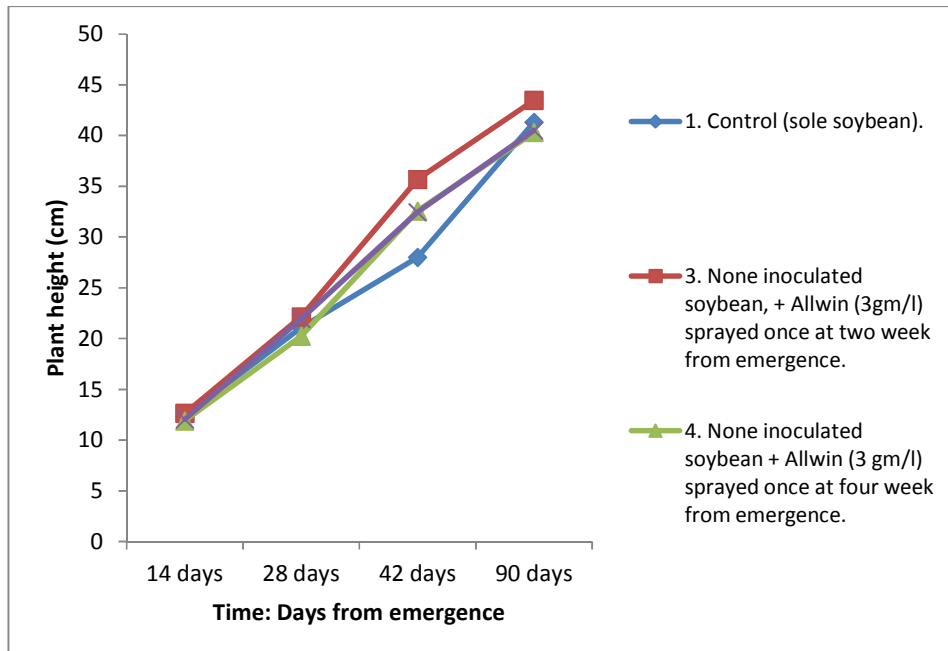
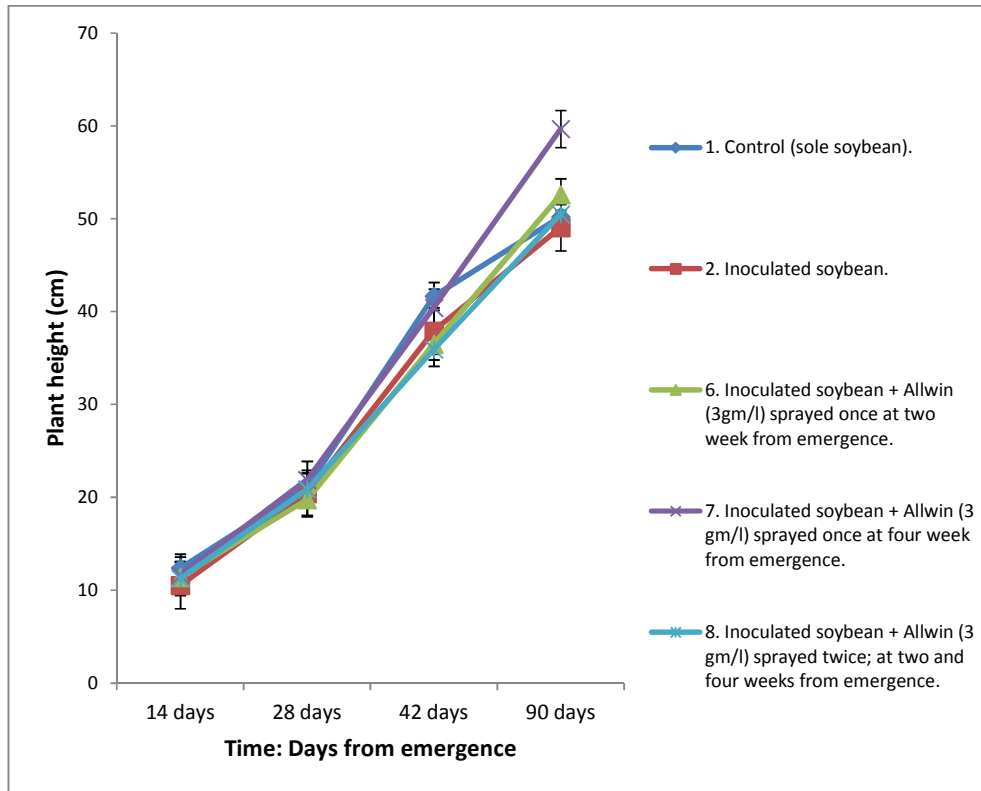
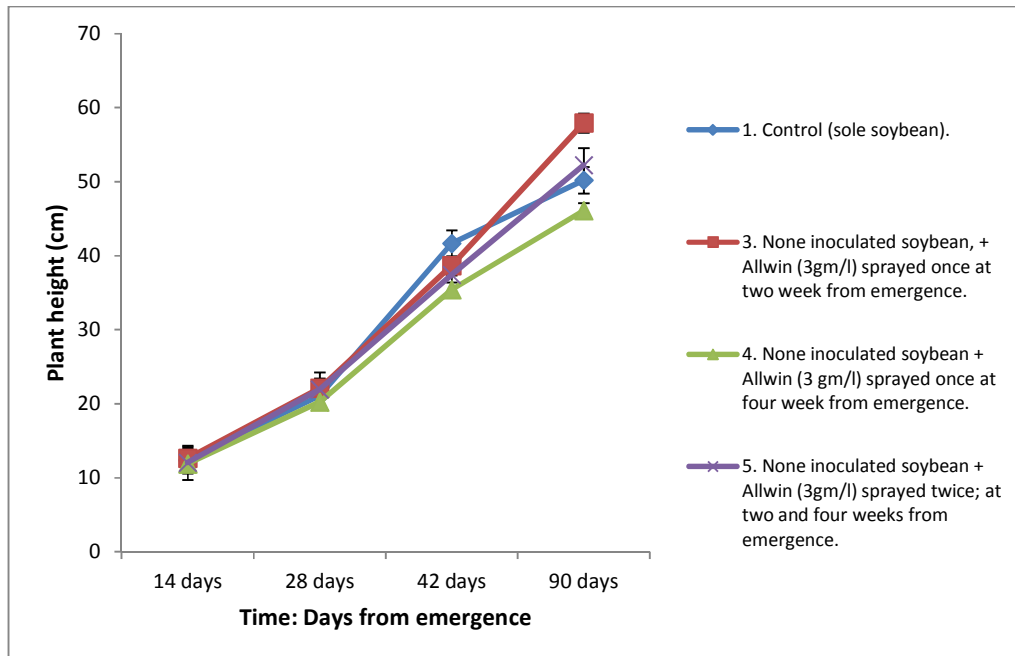


Fig. 7. The effect of sole foliar application of Allwin fertilizer (legumes) on soybean growth rate





**Fig. 8. The effect of combining soybean inoculation with the foliar application of Allwin fertilizer (legumes) on soybean growth rate**



**Fig. 9. The effect of sole foliar application of Allwin fertilizer (legumes) on soybean growth rate**

was observed at about thirty fifth and forty second day from emergence but declined after day forty two from emergence.

### 3.2 Nodulation of Soybean

#### 3.2.1 Nodulation of soybean at Bvumbwe agricultural research station at six weeks from emergence

Table 4 shows the effect of combining inoculation of soybean and foliar application of Allwin fertilizer on nodulation at Bvumbwe Agricultural Research Station. Data at six weeks from emergence indicated that combining inoculation with application of Allwin foliar fertilizer once at two weeks or four weeks or twice at two and four weeks from emergence did not depress nodule development and effectiveness. Treatment seven (inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) and eight (inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) had significantly higher ( $p < 0.05$ ) number of

effective nodules compared with the control. However treatment six (inoculated soybean that was treated with Allwin foliar fertilizer (legumes) at two weeks from emergence) and treatment two (inoculated soybean) had insignificantly higher ( $p > 0.05$ ) number of effective nodules compared with the control. No significant differences ( $p > 0.05$ ) were observed on mass of nodules across treatments. The mass of nodules ranged from 0.7-0.9 g/plant.

For non-inoculated treatments, data at six weeks from emergence indicated that application of Allwin foliar fertilizer once at two weeks or four weeks or twice at two and four weeks from emergence did not depress nodule development and effectiveness. Treatment three (non-inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence) and five (non-inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) had significantly higher ( $p < 0.05$ ) number of effective nodules compared with the control. However treatment four (non-inoculated

**Table 4. Effect of combining inoculation of soybean and foliar application of Allwin fertilizer on nodulation at Bvumbwe Agricultural Research Station**

Treatments	Number of nodules plant <sup>-1</sup>	Effective nodules plant <sup>-1</sup>	None effective nodules plant <sup>-1</sup>	Mass of nodules plant <sup>-1</sup> (g)
1. Control (sole soybean).	32	15	17	0.69
2. Inoculated soybean	29	23	6	0.69
3. None inoculated soybean, + Allwin (3gm/l) sprayed once at two week from emergence.	39	24	15	0.91
4. None inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	42	23	19	1.08
5. None inoculated soybean + Allwin (3gm/l) sprayed twice at two and four weeks from emergence.	40	26	14	0.84
6. Inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence.	34	18	16	0.73
7. Inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	37	24	13	0.73
8. Inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	39	26	13	0.89
LSD <sub>0.05</sub>	15	9	10	0.37
CV%	6.2	13	25.4	4.2

**Table 5. Effect of combining inoculation of soybean and foliar application of Allwin fertilizer on nodulation at Chitala Agricultural Research Station**

Treatments	Nodules plant <sup>-1</sup>	Effective nodules plant <sup>-1</sup>	None effective nodules plant <sup>-1</sup>	Mass of nodules (g)
1. Control (sole soybean).	6	3	3	0.1
2. Inoculated soybean	9	5	4	0.2
3. None inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence.	16	10	6	0.2
4. None inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	7	5	2	0.1
5. None inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	10	6	4	0.3
6. Inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence.	7	4	3	0.2
7. Inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	7	4	3	0.1
8. Inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	14	10	4	0.3
LSD <sub>0.05</sub>	11	8	2	0.1
CV%	36.6	43.7	18.3	30.6

soybean + Allwin (3 gm/l) sprayed once at four week from emergence) had none significantly higher ( $p>0.05$ ) number of effective nodules compared with the control. Generally, no significant differences ( $p>0.05$ ) were observed on mass of nodules across treatments. The mass of nodules ranged from 0.7-1.1 g/plant.

### 3.2.2 Nodulation of soybean at Bembeke sub-agricultural research station at six weeks from emergence

Soybean nodulation at Bembeke sub-Agricultural Research Station at six weeks from emergence was very poor across all treatments. Number of nodules ranged from 1-3 per plant. However the few nodules, largely, were all effective.

### 3.2.3 Nodulation of soybean at Chitala agricultural research station six weeks from emergence

Table 5 shows the effect of combining inoculation of soybean and foliar application of Allwin fertilizer on nodulation at Chitala Agricultural Research Station. Nodulation of soybean at Chitala Agricultural Research Station at six weeks from emergence was less prolific compared with nodulation of soybean at Bvumbwe Agricultural Research Station. However, no significant differences ( $p>0.05$ ) in the number of nodules, effective nodules and

nodule mass per plant were observed across treatments. Number of nodules at the time ranged from 5 to 14 per plant, number of effective nodules ranged from 4 to 13 nodules per plant while mass of nodules ranged from 0.1 to 0.3 g per plant.

## 3.3 Soybean Yields

### 3.3.1 Soybean yields at Bvumbwe Agricultural Research Station

Table 6 shows the treatment effect on soybean yields at Bvumbwe Agricultural Research Station at harvest.

Upon foliar application of Allwin fertilizer (legumes) alone, the result indicate that treatment four (none inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) seemed to have significantly ( $p<0.05$ ) increased the number of soybean pods/plant above the control. While treatments three (none inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence) and five (none inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence) appeared to have increased the number of soybean pods/plant insignificantly ( $p>0.05$ ) above the control. Additionally seed size, measured by the weight of 100 seeds, seemed not to have been affected by foliar application of

Allwin fertilizer. However, on grain yield, treatment three (none inoculated soybean, + Allwin (3gm/l) sprayed once at two week from emergence) and five (none inoculated soybean + Allwin (3gm/l) sprayed twice; at two and four weeks from emergence) produced significantly higher yields ( $p < 0.05$ ) above the control.

While upon combining inoculation with foliar application of Allwin fertilizer (legumes), the result indicate that treatment eight (inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) seem to have significantly ( $p < 0.05$ ) increased the number of soybean pods/plant above the control. While treatments two (inoculated soybean) and six (inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence) and seven (inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) appeared to have produced none significant ( $p > 0.05$ ) increase in the number of soybean pods/plant above the control. Additionally seed size, measured by the weight of 100 seeds, seemed to have been significantly increased ( $p < 0.05$ ) by combining inoculation with foliar application of Allwin fertilizer in treatments two, six and eight,

above the control. Furthermore, on grain yield, treatment eight (inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) and six (inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence) produced significantly higher yields ( $p < 0.05$ ) above the control. The grain yields however were none significantly ( $p > 0.05$ ) higher above the control in treatment two (inoculated soybean) and seven (inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence).

### 3.3.2 Yields for soybean at Bembeke

Table 7 shows the treatment effect on soybean yields at Bembeke Agricultural Research Station at harvest.

Upon foliar application of Allwin fertilizer (legumes) alone, the result indicate none significant differences ( $p > 0.05$ ) in the number of pods/plant across treatments. Additionally seed size, measured by the weight of 100 seeds, seemed not to have been affected by foliar application of Allwin fertilizer. However, on grain yield, treatment three (none inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from

**Table 6. Yields for soybean at Bvumbwe**

Treatment	Number of pods plant <sup>-1</sup>	Grain yield (kg ha <sup>-1</sup> )	Standing biomass (kg ha <sup>-1</sup> )	100 grain Weight (g)
1. Control (sole soybean)	26 <sup>c</sup>	3,048 <sup>c</sup>	4,209	14.0 <sup>b</sup>
2. Inoculated soybean	30 <sup>bc</sup>	3,310 <sup>bc</sup>	4,034	15.0 <sup>a</sup>
3. None inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence	35 <sup>abc</sup>	4,107 <sup>ab</sup>	4,015	14.0 <sup>b</sup>
4. None inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence	39 <sup>ab</sup>	3,890 <sup>bc</sup>	3,726	14.0 <sup>b</sup>
5. None inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence	32 <sup>bc</sup>	4,605 <sup>a</sup>	4,154	14.0 <sup>d</sup>
6. Inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence.	29 <sup>bc</sup>	4,210 <sup>ab</sup>	3,368	15.0 <sup>a</sup>
7. Inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	33 <sup>bc</sup>	3,815 <sup>bc</sup>	4,625	14.0 <sup>b</sup>
8. Inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence	43 <sup>a</sup>	4,076 <sup>ab</sup>	3,976	15.0 <sup>a</sup>
LSD <sub>0.05</sub>	10	611	1,087	1.0
CV%	13.9	10.6	5.3	4.6

emergence), four (none inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) and five (none inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) produced significantly higher yields ( $p < 0.05$ ) above the control. Whilst upon combining inoculation with foliar application of Allwin fertilizer (legumes), the result indicate none significant differences ( $p > 0.05$ ) in the number of pods across treatments. Generally, seed size, measured by the weight of 100 seeds, seemed not to have been affected by foliar application of Allwin fertilizer. However, on grain yield, treatment six (inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence), seven (inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) and eight (inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) produced significantly higher yields ( $p < 0.05$ ) above the control.

### 3.3.3 Yields for soybean at Chitala

Table 8 shows the treatment effect on soybean yields at Chitala Agricultural Research Station at harvest.

In treatments where Allwin was applied without inoculation, significant differences ( $p < 0.05$ ) in the

number of pods/plant across treatments were observed, with treatments three (none inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence) and five (none inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) having significantly higher number ( $p < 0.05$ ) of pods/plant above the control. Generally, seed size, measured by the weight of 100 seeds, seemed not to have been affected by foliar application of Allwin fertilizer. On grain yield, treatment two (none inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence), four (none inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) and five (none inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) produced significantly higher yields ( $p < 0.05$ ) above the control. However, treatment four (none inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) had significantly lower yield ( $p > 0.05$ ) compared with treatment five (none inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) but comparable to yield produced in treatment three (none inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence).

**Table 7. Yields for soybean at Bembeke**

Treatments	Number of pods plant <sup>-1</sup>	Grain yield (kg ha <sup>-1</sup> )	Standing biomass (kg ha <sup>-1</sup> )	100 grain Weight (g)
1. Control (sole soybean).	23	1,055 <sup>d</sup>	3,691 <sup>abc</sup>	13 <sup>b</sup>
2. Inoculated soybean.	29	2,319 <sup>cd</sup>	2,758 <sup>c</sup>	15 <sup>a</sup>
3. None inoculated soybean, + Allwin (3gm/l) sprayed once at two week from emergence.	27	2,700 <sup>bc</sup>	4,263 <sup>ab</sup>	14 <sup>ab</sup>
4. None inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	25	2,614 <sup>bc</sup>	3,008 <sup>bc</sup>	14 <sup>ab</sup>
5. None inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	27	3,781 <sup>ab</sup>	4,863 <sup>a</sup>	14 <sup>ab</sup>
6. Inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence.	28	2,989 <sup>bc</sup>	3,460 <sup>b</sup>	14 <sup>ab</sup>
7. Inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	24	3,055 <sup>a</sup>	2,860 <sup>c</sup>	15 <sup>a</sup>
8. Inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	22	4,903 <sup>a</sup>	4,932 <sup>a</sup>	14 <sup>ab</sup>
LSD <sub>0.05</sub>	13.0	1,270	1,340	2
CV%	26.7	20.15	20.43	2.9

**Table 8. Yields for soybean at Chitala**

Treatments	Number of pods plant <sup>-1</sup>	Grain yield (kg ha <sup>-1</sup> )	Standing biomass (kg ha <sup>-1</sup> )	100 grain Weight (g)
1. Control (sole soybean).	20 <sup>c</sup>	1,154 <sup>f</sup>	2,197 <sup>b</sup>	12 <sup>a</sup>
2. Inoculated soybean.	36 <sup>ab</sup>	1,602 <sup>ef</sup>	2,416 <sup>b</sup>	12 <sup>a</sup>
3. None inoculated soybean, + Allwin (3 gm/l) sprayed once at two week from emergence.	39 <sup>ab</sup>	2,548 <sup>bc</sup>	4,360 <sup>a</sup>	12 <sup>a</sup>
4. None inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	22 <sup>c</sup>	2,129 <sup>cde</sup>	2,669 <sup>ab</sup>	12 <sup>a</sup>
5. None inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	38 <sup>ab</sup>	2,865 <sup>ab</sup>	3,200 <sup>ab</sup>	12 <sup>a</sup>
6. Inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence.	34 <sup>b</sup>	2,057 <sup>de</sup>	3,630 <sup>ab</sup>	12 <sup>a</sup>
7. Inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence.	38 <sup>ab</sup>	2,013 <sup>de</sup>	4,267 <sup>a</sup>	11 <sup>b</sup>
8. Inoculated soybean + Allwin (3 gm/l) sprayed twice at two and four weeks from emergence.	40 <sup>a</sup>	3,324 <sup>a</sup>	3,658 <sup>ab</sup>	12 <sup>a</sup>
LSD <sub>0.05</sub>	6.0	475	1,742	1
CV%	10.67	12.95	30.9	5.5

In treatments where Allwin was applied in combination with inoculation of soybean, significant differences ( $p < 0.05$ ) in the number of pods/plant across treatments were observed. In general sole inoculation and combining inoculation with foliar application of Allwin fertilizer either once, that is, at two and four weeks after emergence, or twice, applied at two and four weeks after emergence, produced a significantly higher number ( $p < 0.05$ ) of pods/plant above the control. Overall, seed size, measured by the weight of 100 seeds, seemed not to have been affected by combining inoculation with foliar application of Allwin fertilizer. On grain yield, treatment six (inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence), seven (inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) and eight (inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence) produced significantly higher yields ( $p < 0.05$ ) above the control. However, treatment six (inoculated soybean + Allwin (3 gm/l) sprayed once at two week from emergence) and seven (inoculated soybean + Allwin (3 gm/l) sprayed once at four week from emergence) had significantly lower yield ( $p > 0.05$ ) compared with treatment eight (inoculated soybean + Allwin (3 gm/l) sprayed twice; at two and four weeks from emergence).

## 4. DISCUSSION

### 4.1 Soybean Growth Rate

The soybean field at Bvumbwe, had very high content of available P. Such being the case, root and nodule development was not constrained [23]. This potentially facilitated early N fixation by the legume and efficient nutrient uptake from the soil across all the treatments. The thinly accelerated growth rate observed after the second application in the treatment plot where inoculation was combined with application of Allwin foliar fertilizer twice at two and four weeks, seem to suggest a slightly increased supply of nutrients above other treatments. At Bembeke, the strongly acid soil reaction and the very low to low content of available P in the soil constrained early root development, nodule development and subsequently N fixation and nutrient uptake by the soy bean [24-26]. Resultantly, supplying nutrients through foliar application once at two and four weeks from emergence and twice, at two and four weeks from emergence accelerated soybean growth rate visibly above the control. Noticeably, at about forty two days from emergence, apart from treatment six, growth rate in the treated plots apparently decreased but remained steady in the control treatment, while treatment number three had a more accentuated

growth rate above other treatments. The reason for this is not clear. Visibly, in the control plot, growth rate seemed to have increased towards the maturity of the crop. Attributed to, at that stage, a fairly developed root system, that potentially was accessing more nutrients in the face of increasing nutrient demand by the crop for podding and grain filling. At Chitala Agricultural Research Station, , though soil P was low but the soil reaction was not grossly prohibitive to the general availability of nutrients and root development, but the low soil P status might have limited nodule development and subsequent N fixation by the soybean [23]. As general nutrient availability and root development might not have been wholly affected, nutrient uptake by the crop from the soil may not have been severely constrained across all treatments. Therefore, absence of accelerated growth after foliar feeding of the nutrients by the crop in treated plots might suggest the presence of other biophysical growth limiting factors in this environment. Notwithstanding the above, generally uneven growth rate/pattern was observed. The observation is attributable the potential presence of a variable soil fertility gradient at the site.

#### 4.2 Nodulation of Soybean

Nodulation of soybean at Chitala Agricultural Research Station was less prolific compared with nodulation of soybean at Bvumbwe Agricultural Research Station across all treatments, but much better compared to nodulation of the crop at Bembeke. Soil factors might be responsible for the observed trend. Primarily, soil pH was acid. It is likely, the acid soil environment impinged on nodulation. Secondly, the field's total N content was high between 0-20 cm and low within 20-40 cm, potentially, the activity of rhizobia between 0-20 cm was decreased in the presence of high N content in the soil. Available P, which was very low across the field, compounded the above-mentioned soil fertility constraints, culminating into less prolific nodulation and effectiveness across treatments. A common soil fertility challenge under low soil pH is  $Al^{3+}$  toxicity that cripples root growth [23]. Soil acidity reduces the numbers of nodules on roots of most legumes by over 90% and nodule dry weight by over 50% [24-26]. At Bvumbwe Agricultural Research Station, the potential presence in the soil of superior indigenous strains of rhizobia in the presence of adequate supply of available P in the soil resulted into effective nodulation across treatments. Phosphorus plays critical roles in

nodule initiation, growth, and functioning apart from the role the nutrient plays in plant growth. However, the number of effective nodules was significantly higher above the control when inoculation was combined with foliar feeding. This suggests a potential stimulation in soybean growth by foliar application of nutrients in the treated plots over the control rather than influence on rhizobia growth and survival or on nodule growth and functioning. Crop growth and development was enhanced both under the sole inoculated treatment and inoculation and foliar feeding of nutrients, thus underscoring the fact that the nutrients supplied through foliar application may have aided root and nodule development and functioning. It is on record that application of conventional fertilizer at 23 kg N ha<sup>-1</sup> as basal dress and application of the same at the rate of 23 kg N ha<sup>-1</sup> at the end of flowering does not inhibit soybean nodulation [22]. Timing of external nutrient application in nutrient interaction experiments is critical, as there is a lag between the times of initial root infection by rhizobia, whether from indigenous populations present in the soil or from inoculation with inoculants and the time that nodules become functional in N<sub>2</sub> fixation. This was reflected in the treatment with Allwin foliar fertilizer sprayed once at four week from emergence that increased the number of effective nodules compared with the control, while the other Allwin treated plots registered significantly higher numbers of effective nodules. Soybean nodulation at Bembeke sub-Agricultural Research Station at six weeks from emergence was very poor across all treatments. Number of nodules ranged from 1-3 per plant. However the few nodules, generally, all were effective. Largely the soil pH at Bembeke is strongly acid. It is established that as soil pH drops below 6, the conditions can become too acidic for rhizobia to effectively create nod factor and form nodules [23]. Potential for Rhizobia survival to be adversely affected under such conditions is high. Additionally under low soil pH, important micronutrients, like molybdenum, that are cofactors for nitrogen fixation may become unavailable [23].

#### 4.3 Soybean Grain Yields

Across the sites, sole application of nutrients to soybean through Allwin fertilizer once at two week from emergence and twice at two and four weeks from emergence increased grain yields by 51.1-258.4% above the control. Similarly, combining inoculation with foliar application of

Allwin fertilizer once at two week from emergence and twice at two and four weeks from emergence increased grain yields by 33.7-364.7% yields above the control. The results are in tandem with findings by [27] who reported that inoculation and fertilizer use promote plant growth and increase grain yields in soybean. Furthermore, other studies have demonstrated that, using conventional fertilizer, legumes have a highly significant response to small N doses (20–30 kg N ha<sup>-1</sup>) [28]. Generally, basing on plant biomass and nodulation data, at Bembeke and Chitala where available P was low nodulation was more sensitive to P deficiency than general plant growth, a pattern similar to the trend reported by [29]. Intriguingly, the highest grain yield response was obtained at Bembeke, a location with harsh soil pH and weather conditions. This underscores the significance of foliar application of plant nutrients under conditions of low soil fertility.

## 5. CONCLUSION

Generally, in adverse soil conditions under the changing climate, application of nutrients to soybean through foliar feeding produced significantly higher yields above the control across different agro-ecological zones. The result underscores the importance of judicious and methodical application of nutrients to soybean under low soil fertility and varying climatic conditions. The work has demonstrated that external N supply to soybean is imperative under acid and low soil P environments since nodulation and subsequently BNF is constrained in such environments. In general, foliar application of nutrients particularly when conducted twice can increase significantly soybean productivity in Malawi. The yield increases is attributable to the stimulation of root, shoot growth, and enhanced dry matter production and its partitioning by foliar supply of nutrients to the soybean. Edaphic factors, like soil acidity and inherent nutrient contents as well as the climate have proved to be key regulators of growth and yield response of the soybean to foliar feeding.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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