Enhancing common bean tolerance to short-term droughts at the reproductive stage using a soil fertility management approach

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Abstract

Aims: This study was conducted to enhance the tolerance of common beans to drought events occurring at the reproductive stage, from a soil improvement perspective.

Study design: Split plot completely randomized design was used.

Place and duration of study: Study was conducted in a screen-house at the Legumes and Oil Seeds Division of CSIR-Crops Research Institute, Ghana, from September 2021 to January 2022.

Methodology: Municipal Solid Waste Compost and inorganic fertilizer combinations were applied to common beans in a pot experiment. They included control, full rate compost (FRAC), full rate fertilizer (NPK 5:30:30 kg/ha) (FRG), FRG + half rate compost (HRAC) and FRG + FRAC. All soils were maintained at 80% field capacity (FC) from the start of the experiment. At flowering, two groups of plants were water stressed till 40 and 16% FC and returned to 80% FC till physiological maturity, while one group maintained 80% FC throughout study. Forty-five soil samples each and plant data were collected at 3, 7 and 10 weeks after planting. Samples were analyzed for soil organic matter (SOM) and water retention, soil nutrients, crop growth, yield and nutrient uptake. Water and nitrogen use efficiencies (W/NUE) were calculated after harvest.

Results: During the growing period, highest soil moisture (6-9 cm^3/cm^3) was retained by FRG and FRG+HRAC, FRG+FRAC; 20-38% more than FRAC and control but was not influenced by SOM. While FRG influenced the highest yield and WUE, combining it with compost rates reduced yield by 56-84% and WUE by 55-64%. WUE correlated positively with NUE.

Conclusion: Antagonistic effect observed with integrating compost with FRG is likely because compost was not properly cured and immobilized soil nitrogen. Farmers can mitigate short-term drought effects on common beans with adequate nutrient supply through fertilizer application; however, fertilizer should only be integrated with compost after compost quality analysis.

Keywords: compost, mineral fertilizer, water stress, soil organic matter, soil water retention, water use efficiency, climate change

1. INTRODUCTION

Legumes account for 27% of global primary crop production and 33% of global protein requirement [1]. They are major cash crops for more than 700 million smallholder farmers in developing countries and can be grown in a variety of climates and soil types [1]. They fix atmospheric nitrogen in the soil and may reduce the required amounts of chemical nitrogen fertilizers needed per application. Hence they are one of the most promising crops to promote climate smart agriculture [2].

Common beans (*Phaseolus vulgaris* L.), the most important food legume for direct consumption, contribute about 8.8% to the global annual total legume value of 31 billion USD [3]. Though an important legume, about 60% of common bean production occurs under short-term or terminal drought stresses [4]. In Ghana, legumes (common bean included) are widely cultivated in the Savannah agroecological zones of the country where short and long term droughts are common occurrences [5, 6]. Drought stress is a major constraint to common bean production in Ghana and many other countries and results in about 10% to 100% yield losses globally [7]. A 70% reduction in common bean yield due to drought stress in Colombia was observed by [8]. An 80% decrease in common bean seed yield at very severe drought (drought intensity index of 0.8) was also reported by [9]. As a result, drought coping mechanisms have become key traits for common bean germplasm selection and for improving productivity of the crop [10].

Plants may use various mechanisms to cope with drought stress. These mechanisms may be grouped into drought tolerance, drought avoidance, and drought escape. The drought tolerance mechanism allows plants to adjust cell osmosis, plasticity and size and produce organic solutes like proline to protect cells from damage caused by water stress [11, 12]. In drought avoidance, plants maintain relatively higher tissue water potential even when surface soil moisture decreases below optimal levels. They may achieve this through deep rooting systems, reduction of radiation absorption in leaves and reduction in hydraulic conductance [13]. The drought escape mechanism involves an accelerated plant cycle through flowering and maturity [7]. It is the ability of the crop to rapidly allocate photosynthates to reproductive structures before the onset of a drought [14].

Environmental and genetic factors interact to confer drought resistance on plants [15], and one or both factors could be manipulated to enhance any of the afore-mentioned mechanisms in common beans. Soil is a common environmental factor that affects the drought resistance of common beans. The soil's available water capacity (AWC) is an important control on the amount and length of time it can retain water for plant use, and is an effective soil property to manage crop drought resistance, especially in short- term droughts [16, 17]. An increase in soil organic matter (SOM) may increase soil water retention at field capacity and relatively increase AWC [18, 19]. A relatively higher soil water retention capacity implies that crops would have relatively longer access to water for growth.

Poor soil fertility is another major soil constraint to legume production and common bean drought tolerance in Ghana and sub-Saharan Africa [20, 21]. In many small-holder farms, legumes are cultivated without external inputs [22, 23]. Though common bean fixes between 2-28 kg/ha nitrogen annually through biological nitrogen fixation (BNF) [24], a proper crop growth requires adequate supply of all other essential nutrients. Previous studies have found up to 80% improvements in common bean yield with phosphorus and potassium fertilizer applications [25, 26, 27]. An adequate supply of nutrients may enhance the drought tolerance of common beans because water-nutrient interactions impact water use and productivity at all levels of crop growth [28, 29, 30]. Crops with adequate nutrient supply often show higher drought tolerance [31] because of the increase in water use efficiency (WUE) [32]. Water use efficiency is the amount of biomass or grain produced per unit water transpired or applied in irrigation. Thus, when soil moisture and nutrients are adequately supplied, water aids mass flow and transport of nutrients to roots. Water uptake by the roots to meet transpiration needs simultaneously takes up soil nutrients [33].

In this study, improving soil organic matter (which controls soil water retention) and nutrient concentrations were the focal points to manage drought resistance of common beans. To address these problems, we explored the integrated use of fertilizer and compost. Integrated fertilizer and organic soil amendment use has been recommended by [34] because of the ability of the two resources to jointly supply soil nutrients and improve soil physical properties. Hence the objective of the study was to supply essential nutrients to common beans through fertilizer application while compost improved soil organic matter and consequently soil water retention to mitigate the effects of drought on common beans. The study imposed drought at the flowering to pod-setting period of common bean growth because that is the most sensitive period to drought stress [35, 36]. Many drought tolerant studies have confirmed 80% field capacity (FC) moisture as the optimum moisture level for common bean production [37, 38, 10]. Drought stress up to 16% FC, reported in a previous study [10] was followed to avoid bringing common bean plants to permanent wilting points. Periodic soil moisture, soil nutrients, plant growth and yield data were collected over time to achieve the objective of the study.

2. MATERIALS AND METHODS

2.1 Study site

The research was conducted in a screen house at the Legumes and Oil Seeds Division of the CSIR-Crops Research Institute (CRI), Fumesua in the Ashanti Region of Ghana from September 2021 to January 2022. CSIR-CRI is situated at Latitude 6.7 109^{o}N, Longitude 1.5172^{o}W, and 800 m above sea level. It is in the semi-deciduous forest agro-ecological zone (CSIR-CRI weather station). The area has a bi-modal rainfall pattern, with a mean annual rainfall of about 1550 mm. The major rainy season starts from April to the end of July, followed by a dry spell in August, while the minor rainy season continues from September to November every year. Annual temperatures range from a minimum of 21.1^{o}C to a maximum of 32.7^{o}C and a mean of 31.6^{o}C.

2.2 Activities before experimental set-up

The soil's bulk density was determined on a field previously planted to legumes. Soil was collected from this field, sterilized and its field capacity moisture determined before the experimental set-up. Soil samples and compost samples were taken for initial analyses and characterization. Five holes of about 2 cm diameter were perforated at the bottom of the buckets. Buckets were filled with sterilized soil. The procedures outlined below were followed:

2.2.1 Soil bulk density determination

Three core samplers (cylindrical in shape) were used to collect soil from the field. The core samplers with the soil were weighed and put in an oven at 105^{o}C for two days. After two days, the dried soil samples with the core samplers were weighed. Bulk density was calculated by the formula below:

Bulk density = $\frac{\text{mass of dry soil}}{\text{volume of core sampler}}$ equation 1 [39]

Mass of dry soil = *weight of core sampler with oven-dried soil (after cooling down) – weight of core sampler* equation 2

The volume of a core sampler was determined by the formula of the volume of cylinder as follows:

Volume of core sampler = $\pi r^2 h$ equation 3

Where $\pi = 22/7$; r is the radius of the circular end of the core sampler; h is the height of the core sampler. The average bulk density of soil in the three core samplers was determined.

2.2.2 Soil sterilization

Field soil was collected, thoroughly mixed, filled into barrels and heated over an LPG flame while covered with jute sacks and a lid. The temperature of the soil was monitored with a thermometer on the top of the soil until it reached 100°C. The soil was left to heat on the flame after the 100°C point for three more hours. The prescribed sterilization method [40] was done to combat nematodes and other soil-borne pathogens.

2.2.3 Field capacity moisture determination

Three polyvinil chloride (PVC) pipes of 25 cm length and 11 cm diameter were marked at 15 cm length. They were taken to the field where soil was collected and pushed down carefully to the 15 cm mark (thus a soil depth of 15 cm was collected).Circular trenches were dug around the pipes to 15 cm depth to enable us carefully carry the PVC pipe with the full depth of soil at the bottom of the pipe with a hand trowel. This was done to ensure that the bulk density of the soil is not altered. The bottom ends of the PVC pipes with soil were covered with plastic netting material and sent to a greenhouse. The soil was flooded with 1 L of tap water from the other open end. The water drained through the net after about 30 seconds of pouring it. The PVC pipes were left on a greenhouse bench for two days with the covered net side raised on two slabs of wood sitting on the greenhouse bench. Gravimetric soil moisture determination was done after two days when no water was visibly draining from the soil through the net. Volumetric soil moisture determination was done with an instant moisture meter. Ten grams of the soil from each pipe was oven dried at 105°C for two day to determine gravimetric soil moisture as follows:

Gravimetric soil moisture (g/g) = $\frac{\text{weight of fresh soil (g)} - \text{weight of dry soil (g)}}{\text{weight of dry soil (g)}}$ equation 4 [41]

2.2.4 Filling buckets with soil to simulate field bulk density

Gravimetric soil moisture of the sterilized soil was determined. The sterilized soil was used to fill the buckets to 15 cm depth. The buckets measured 18 cm deep and 20 cm in diameter (buckets were cylindrical in shape).The weight of dry soil to fill up to the 15 cm mark was calculated to simulate the field bulk density. The filling depth and radius of the buckets were used to calculate the filling volume. Mass of soil used to fill bucket was calculated as follows:

Dry mass of soil (g) = Bulk density of field soil (g/cm^3) × filling volume of the bucket (cm^3) equation 5 [39]

Filling volume of the bucket = $\pi r^2 h$ equation 6

Where π = 22/7; r is the radius of the circular end of the bucket; h is the filling height (15cm) of soil.

To account for moisture content of the sterilized soil in order to fill the exact dry soil weight:

Fresh sterilized soil weight (g) = $\frac{\text{dry mass of soil (g)} \times 100\%}{(100\% - \text{gravimetric soil moisture\%})}$ equation 7

The soil was pressed to the 15 cm mark after filling and left to settle for two weeks while buckets were covered with lids. The buckets were arranged on the screen house floor.

2.3 Initial soil and compost sampling and analyses

Three samples were collected from the sterilized soil (about 100g each) for initial analyses. Three Municipal Solid Waste (MSW) Compost samples were also analyzed and characterized. The soil was analyzed for pH [42], organic carbon/matter (OC/M) [43], mineral nitrogen (NO_3^-, NH_4^+) [44], Bray P-1 phosphorus (P) [45] and particle size distribution (texture) [46]. Compost was also analyzed for organic carbon [43], total N [47], P [48] and K [49], spelt out in Table 1 below.

Table 1. Characteristics of soil and MSW compost before the start of the experiment

	pH	NO_3^-	NH_4^+	Avail. P	OC	OM	Total N	Total P	Total K	Texture
		mg/kg			%					
Soil	6.21	71.95	48.57	33.72	1.79	3.09	-	-	-	Loamy sand
Compost	5.48	-	-	-	38.17	66.96	1.65	0.86	0.79	

C:N ratio of compost is 23.13

2.4 Experimental design and treatments

Split plot in completely randomized design was used in this study. Treatments were moisture regimes (the main plot factors) and fertility treatments (the sub-plot factors). The levels of moisture regime/drought stress included D1- 80% FC throughout the growth period till physiological maturity; D2 - 80% FC from sowing till flowering; water stress from flowering till 40% FC and re-wetting to 80% FC till physiological maturity; and D3 - 80% FC from sowing till flowering; water stress from flowering till 16% FC and re-wetting to 80% FC till physiological maturity. (The only exception to the moisture regimes happened a day before drought imposition, when all the buckets were saturated with water (methodology adopted from

[10]). The levels of the fertility treatments were control, full rate glycine mix NPK legume fertilizer (FRG), full rate compost (FRAC), full rate glycine mix + half rate compost (FRG + HRAC) and full rate glycine mix + full rate compost (FRG + FRAC). The compost used in this study was made from a collection of municipal solid waste. There were 15 treatments in total. The treatments were replicated thrice to make a total of 45 buckets.

2.4.1 Application of treatments

Buckets were labelled with their designated treatments after randomizing them on the screen house floor. Compost was applied at 4 t/ha, one month before planting. Compost was weighed and mixed with a gardener's fork to about 4 cm depth. Weights of compost to apply were calculated as follows:

Weight of compost = $\frac{4\text{ t} \times (\text{top surface area of soil in bucket})\text{m}^2}{10000\text{ m}^2}$ equation 8

Where 4t represents the rate per hectare; 10000 m^2 is the area of a hectare.

Surface area of the soil = πr^2 equation 9

Where $\pi = 22/7$; r is the radius of the circular open end of the bucket.

Fertilizer was applied at 4 g/plant in two splits. Two grams per plant was applied at two weeks after planting and the other 2 g/plant at pod initiation (48 days after planting, thus after returning from drought imposition). The fertilizer contains a proportion of 5:30:30 kg/ha N:P_2O_5:K_2O. The fertilizer was applied by band placement at 3 cm depth and a distance of 5 cm away from the plant, and well covered with soil.

2.4.2 Planting of common beans

Before planting, 100g of *Enepa* common bean variety (a white seeded common bean variety released by the Legumes and Oil Seeds Division of CSIR-Crops Research Institute in Kumasi-Ghana, in 2016) seeds were soaked with tap water for an hour. The seeds were inoculated with 5g Sarifix *Rhizobium* inoculum. Seeds were planted at three per pot with the hand to about 3 cm depth and later thinned to two per pot. Each pot was watered with 500 ml of water at planting. Gloves were worn to prevent cross contamination of the soil.

2.4.2.1 Watering regime and drought imposition

Soil moisture was maintained at 80% FC for all the pots from the start of the experiment. An instant moisture meter was used to estimate volumetric soil moisture to determine how much water to top-up to

80% field capacity. After five moisture readings and topping up water every two days, it was determined that an average of 125 ml of water was needed to bring the soil to 80% FC every two days.

At the first flower stage (R1 stage), thus 30 days after planting, drought imposition was implemented. A day before drought imposition, soil in all the pots was saturated with 1L of water (adopted from [10]). From that day, soil in pots receiving treatment D1 continued to be maintained at 80% FC. Soil moisture in pots receiving D2 was monitored from the day of saturation till 40% FC. It took 8 days to reach this FC and 80% FC was returned until physiological maturity. Pots receiving treatment D3 was monitored till 16% FC and then returned to 80% FC till harvest. It took 15 days to reach 16% FC.

2.4.2.2 Data collection

Data was collected on volumetric soil moisture, plant height, leaf number, leaf area, Soil Plant Analysis Development (SPAD) chlorophyll (surrogate) concentration of leaves at 3, 7 and 10 weeks after planting (WAP). Data on number of pods, pod weight, number of seeds per pod, seed weight, biomass and soil samples were collected at harvest (71 days after planting). Biomass and soil nutrient statuses were analyzed in the laboratory after harvest. The biomass was analyzed for total nitrogen (N), phosphorus (P) and potassium (K). The soil was analyzed for pH, organic carbon/matter (OC/M), nitrates (NO_3^-) and ammonium (NH_4^+).

2.4.2.3 Harvest

All pods were picked from the plants in the pots into labeled envelopes when the plants were at physiological maturity, 71 days after planting (DAP). The remaining above-ground biomass was cut at root level into labeled envelopes. The samples were oven-dried at 60^{o}C for two days. The pods were weighed and shelled. The seeds were also weighed as g/surface area of soil in the bucket and extrapolated to kg/ha.

2.4.2.4 Nutrient and water use efficiencies

Nitrogen and water use efficiencies were calculated by the following formulae :

$$\text{Nitrogen use efficiency} = \frac{\text{nitrogen uptake in grain yield } \left(\frac{\text{kg}}{\text{ha}}\right)}{[(\text{initial nutrient}+\text{fertilizer nutrient})-\text{residual nutient after harves}]\ \text{kg/ha}} \quad \text{equation 10 [50]}$$

$$\text{Water use efficiency} = \frac{\text{grain yield } \left(\frac{\text{kg}}{\text{ha}}\right)}{\text{amount of irrigation water applied (mm)}} \quad \text{equation 11 [32]}$$

2.5 Statistical analyses

Analyses of variances in the data conferred by the fertility treatments and drought imposition were determined using IBM SPSS statistics 2.0 package. Statistically significant treatment means were separated with Fisher's least significant difference (LSD) at 5% probability. Regression analysis was used to determine relationship between nitrogen and water use efficiencies in Excel.

3. RESULTS

3.1 Periodic soil moisture measurements

Soil moisture was not affected (P>0.05) by drought imposition or its interaction with fertilizer treatments on any of the sampling days. However, the fertility treatments significantly affected soil moisture at 3 WAP (P<0.001), 7 WAP (P<0.001) and 10 WAP (P=0.007). On all the sampling days, FRG, FRG + HRAF and FRG + FRAC affected the highest soil moisture on average (6.9 - 9 cm^3/cm^3) and between 20 to 38% more than compost alone and the control (Fig. 1).

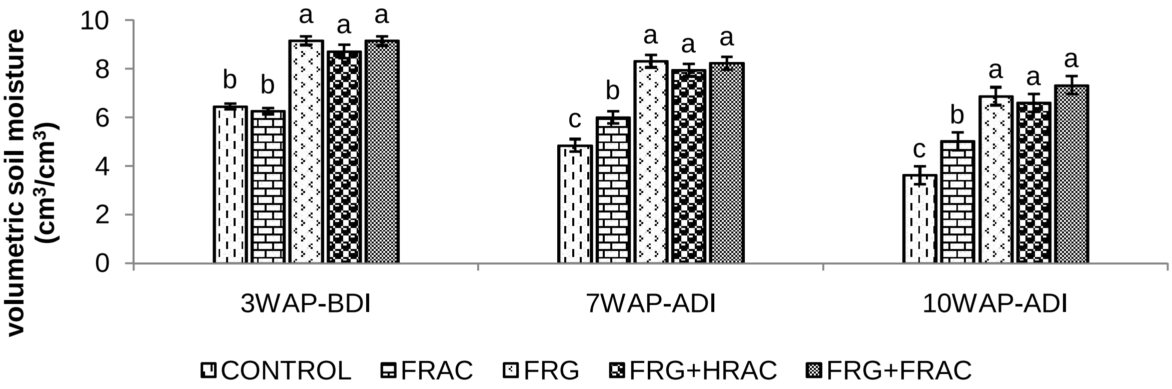


Fig. 1. Volumetric soil moisture (cm^3/cm^3) affected by fertility treatments at 3 WAP (before drought imposition) and at 7 and 10 WAP (after drought imposition). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment means.

3.2 Common bean growth parameters

Plant height was not influenced (P>0.05) by the fertility treatments, drought imposition or their interactions in any of the sampling days.

Fertility treatments affected (P<0.001) leaf number at 3 WAP (before drought imposition) (Fig. 2A). Plants applied with FRG alone had the most number of leaves (12.7) about 10 to 35% more than other amendments. There was 10-24% reduction in leaf number with the addition of half and full rates of the compost to FRG. Interaction between fertility treatments and drought imposition affected (*P*= 0.01) leaf number at 7WAP (after drought imposition) (Fig. 2B). Plants applied with FRG x D2 at flowering had the most number of leaves (40) while plants applied with FRAC x D3 at flowering had the least number of leaves (10). The latter was similar to the number of leaves affected by control x D1; control x D3; FRAC x D1; FRAC x D3; FRG x D3; (FRG + HRAC) x D2. The average number of leaves affected by fertility treatments alone was in the order FRG ≥ (FRG + FRAC) > (FRG + HRAC) > FRAC = Control. Leaf number was not influenced (*P*>0.05) by the fertility treatments, drought imposition or their interactions at 10 WAP.

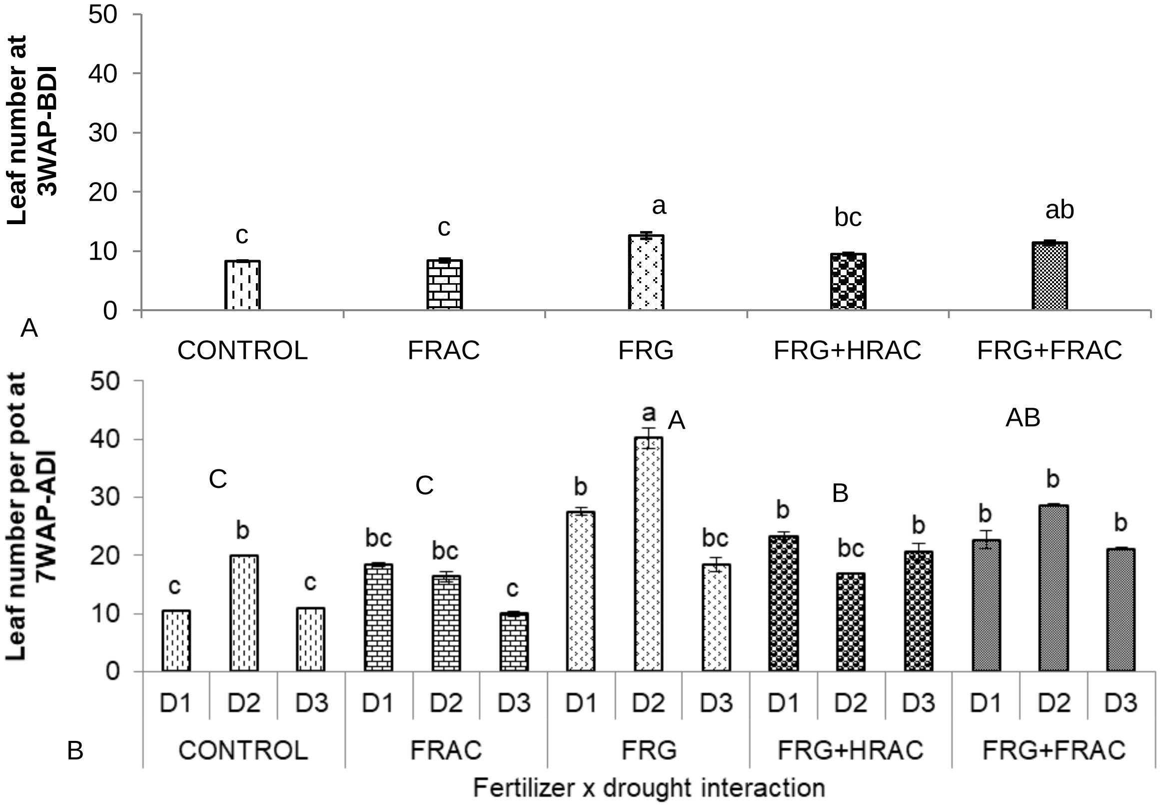


Fig. 2. Leaf number affected by fertility treatments at 3 WAP (before drought imposition) (A); leaf number affected by the interaction between fertility treatments and drought stress at 7 WAP (after drought imposition) (B). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment interaction means. Upper case letters on top of the bars represent significant differences between corresponding fertility treatment means.

Leaf area was affected ($P<0.001$) by fertility treatments at 3 WAP (Fig. 2). FRG affected the highest leaf area between 19-68% higher than the other amendments. The addition of half or a full rate of the compost to FRG reduced leaf area by 19 – 43%. At 7 WAP (after drought imposition), FRG+FRAC affected ($P<0.001$) the largest leaf area which was similar to that affected by FRG. The application of FRG+HRAC, FRAC and control affected the smallest leaf area (Fig. 3). Leaf area at 10 WAP was not affected ($P>0.05$) by fertility treatments, drought stress regimes or their interactions.

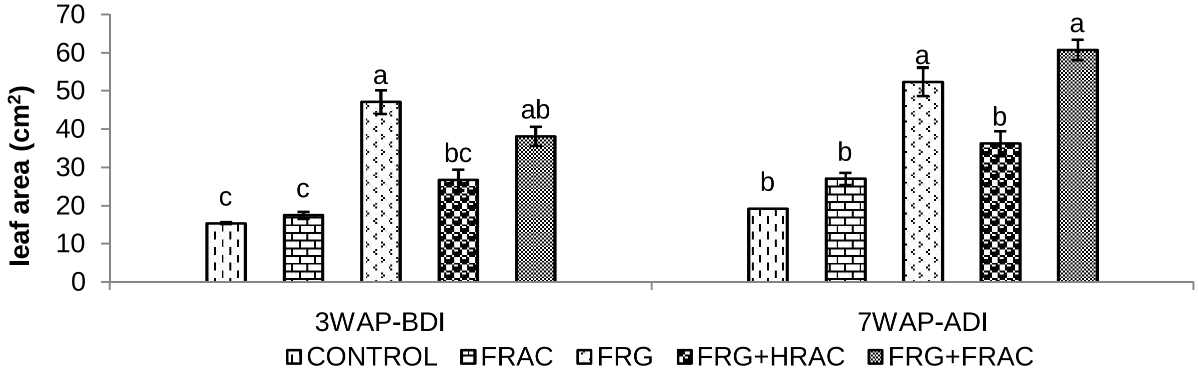


Fig. 3. Leaf area (cm^2) affected by fertility treatments at 3 WAP (before drought imposition) and 7 WAP (after drought imposition). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment means.

SPAD chlorophyll content was affected ($P<0.001$) by fertility treatments at 3 WAP (Fig. 4A). FRG affected the highest leaf chlorophyll concentration (47 SPAD units) which was between 14 – 37% more than other amendments. Leaf chlorophyll was reduced by 14% with the addition of half and full rates of the compost. FRAC and the control affected the least leaf concentration. Leaf chlorophyll concentration was not affected ($P>0.05$) by the interaction of fertility treatments and drought stress regimes at 7 WAI. However, drought regimes affected (*P*=0.02) leaf chlorophyll concentration at 7 WAP (Fig. 4B). D1 and D2 affected the highest leaf chlorophyll concentration (~ 35), about 17% more than D3. Leaf chlorophyll concentration at 10 WAP was not affected (*P*>0.05) by fertility treatments, drought stress regimes or their interactions.

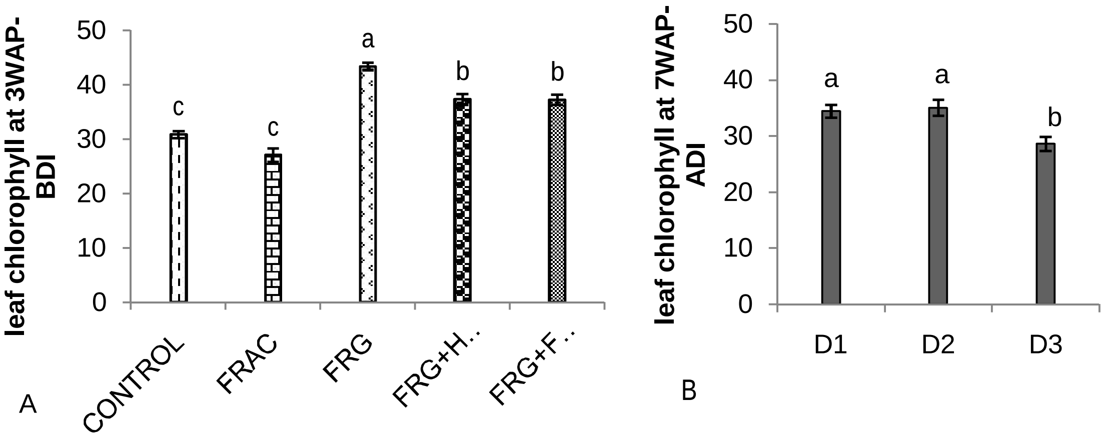


Fig. 4. SPAD leaf chlorophyll concentration affected by fertility treatments at 3 WAP (before drought imposition) (A); leaf chlorophyll concentration affected by drought stress regimes at 7 WAP (after drought imposition) (B). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment means.

3.3 Common bean yield parameters

Grain weight was affected by fertility treatments only (*P*=0.05) but not drought or its interaction with fertility treatments (Fig. 5A). FRG affected the highest grain weight (96 kg/ha). The addition of half and full rates of compost to FRG reduced grain weight by 84 and 56%, respectively. Weights affected by fertility treatments other than FRG were statistically similar.

There was a significant interaction between fertility treatments and imposed drought (*P*=0.008) on common bean dry biomass at harvest (Fig. 5B). FRG imposed with 40% FC drought stress at flowering affected the largest biomass (3055 kg/ha) while the control at 80% FC throughout the study affected the least. On average, FRG alone affected the highest biomass (2037 kg/ha) which was similar to FRG + FRAC but between 48 to 70% higher than biomass affected by FRG + HRAC and other fertility treatments. The control affected 24% higher common bean biomass than compost application alone.

Other yield parameters (number of pods, pod weight, number of seeds) were not affected by fertility treatments, drought imposition or their interactions (*P*> 0.05)

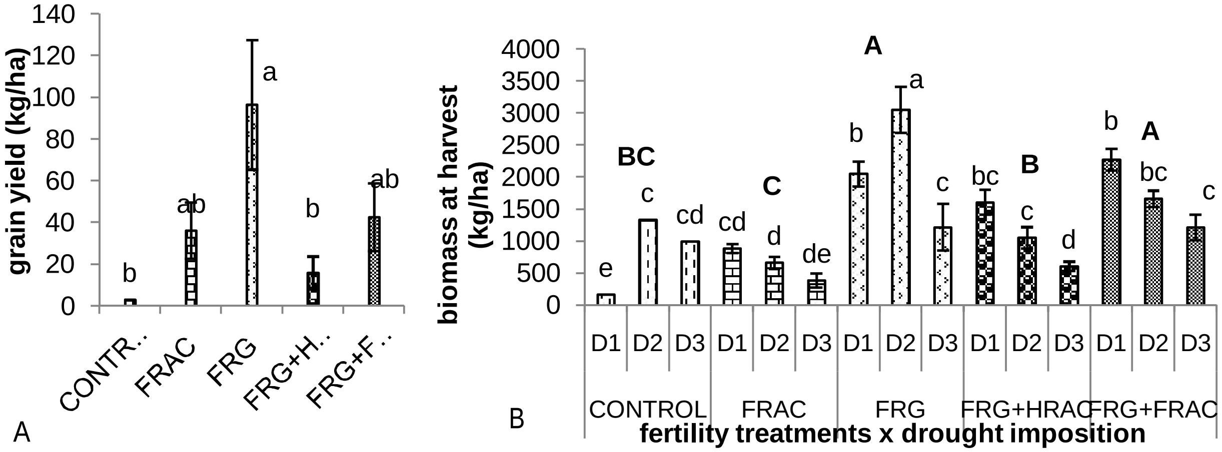
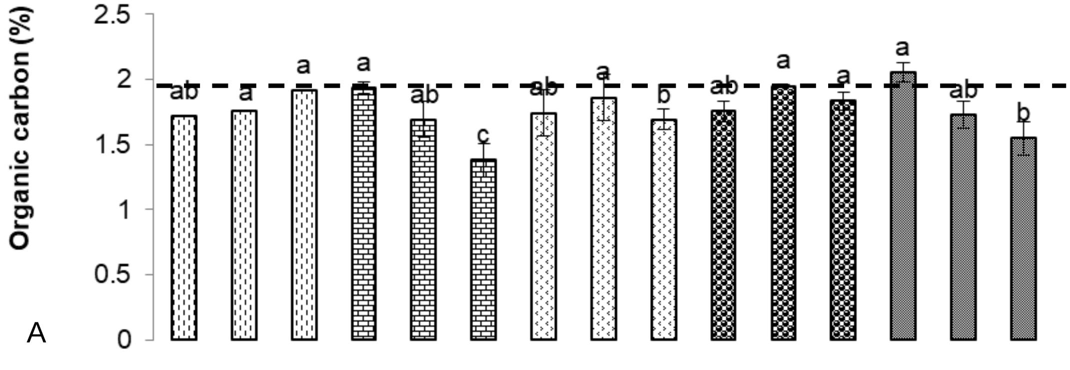


Fig. 5. Grain yield (kg/ha) affected by fertility treatments at harvest (A); biomass (kg/ha) affected by interaction between fertility treatments and drought imposition at harvest (B). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment means (A) and treatment interaction means (B). Upper case letters on top of the bars represent significant differences between corresponding fertility treatment means.

3.4 Soil organic matter and nutrient statuses after harvest

There was significant interaction between fertility treatments and drought imposition on organic carbon (*P*=0.01) and organic matter (*P*=0.01) at the end of the study (Fig. 6 A&B). Control x D2; FRAC x D1; FRG x D2; (FRG+HRAC) x D2 and (FRG+FRAC) x D1 affected up to 7% more organic matter than initial soil organic matter before treatment imposition. However, the application of the fertility treatments alone did not affect (*P*>0.05) soil organic matter but in general soil organic carbon and matter followed the order D1>D2>D3 for drought imposition.



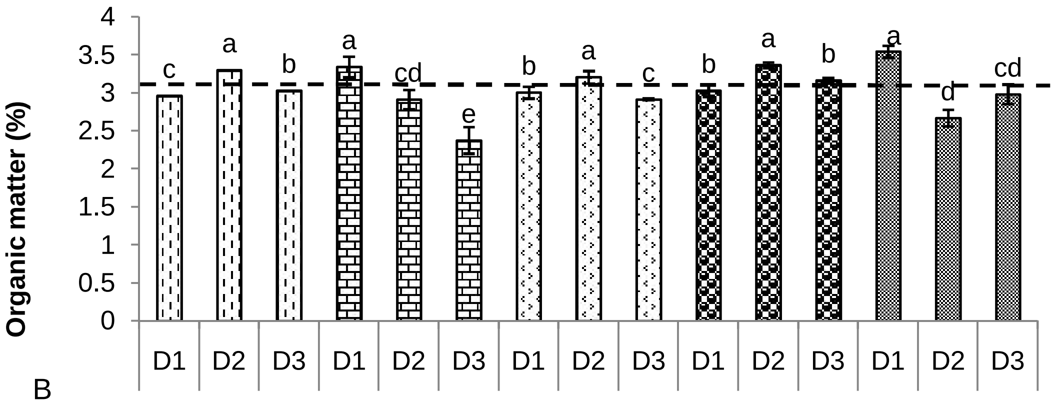


Fig. 6. Organic carbon (%) affected by interaction between fertility treatments and drought imposition at harvest (A); organic matter (%) affected by interaction between fertility treatments and drought imposition at harvest (B). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment interaction means. Short dash lines mark the initial organic carbon and organic matter percentages before treatment imposition.

At the end of harvest, all treatments had residual soil mineral N (NO_3^- + NH_4^+) levels lower than the initial soil mineral N concentration (121 mg/kg). The interaction between fertility treatments and drought imposition significantly affected (*P*<0.005) residual soil mineral N (Fig. 7). FRG treatment with drought imposition at 16% FC (D3) retained the highest soil N concentration (113 mg/kg) which was similar to FRAC x D3; FRG x D1; FRG x D2; (FRG+HRAC) x D1,D2&D3 and (FRG+FRAC) x D1,D2&D3. The control at D3 retained the least amount of soil mineral N (23 mg/kg). On average, FRG, FRG + HRAC and FRG+FRAC retained the highest and similar concentrations of mineral N (~ 95 mg/kg) which was 25-53% more than concentrations retained by FRAC alone and the control. The fertility treatments, drought imposition and their interactions had no effect (*P*>0.05) on residual phosphorus concentration and soil pH.

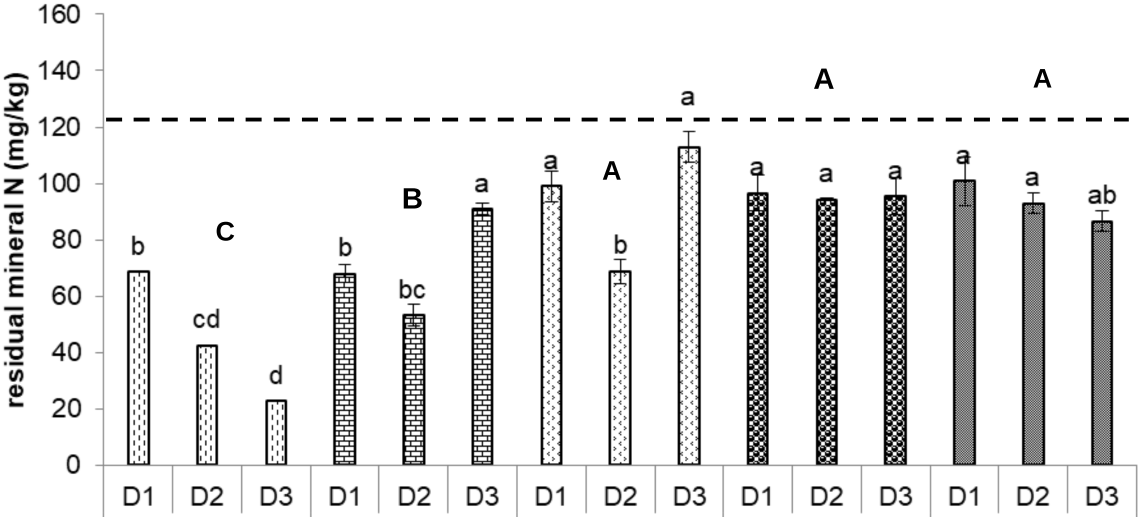


Fig.7. Residual mineral N (mg/kg) affected by interaction between fertility treatments and drought imposition. Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment interaction means. Different uppercase letters represent differences in corresponding fertility treatments (c). Short dash lines mark the initial mineral N concentration before treatment imposition.

3.5 Common bean nutrient uptake

The fertility treatments, drought imposition and their interactions had no effect (*P*>0.05) on plant biomass N and P uptake. However, fertility treatments alone (*P*=0.002) and drought imposition alone (*P*=0.001) affected K uptake in common beans biomass (Fig. 8 A&B). FRG affected the highest K uptake (3%) which was 5 to 18% more than FRAC, FRG+HRAC, FRG+FRAC but was statistically similar to them. Drought imposition to 40% FC at flowering affected 2.7% common bean biomass K uptake, similar to plants that had no moisture stress. However, K uptake was significantly reduced by more than 20% when plants were water stressed till 16% FC at flowering.

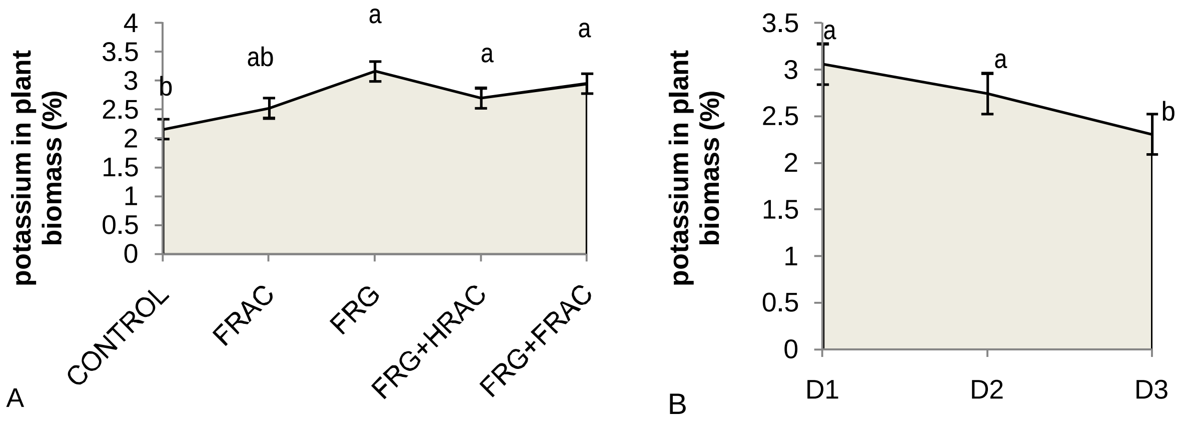


Fig. 8. Potassium uptake (%) in plant biomass as affected by soil fertility treatments (A). Potassium uptake in plant biomass as affected by drought imposition (B). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment means.

3.6 Water use efficiency of common beans

Water use efficiency was affected (*P*=0.05) by the soil fertility treatments. Common bean plants were most efficient with water use with the application of FRG (0.58 kg/ha/mm WUE) (Fig. 9A). Addition of half and full rates of compost to FRG reduced water use efficiency by 55 to 64%. The least efficient water use was affected by the control (0.018 kg/ha/mm) and FRG + HRAC (0.095 kg/ha/mm) (Fig. 9A).

There was a strong positive relationship (R^2=73%) between water use efficiency (WUE) and nitrogen use efficiency (NUE) (Fig. 9B)

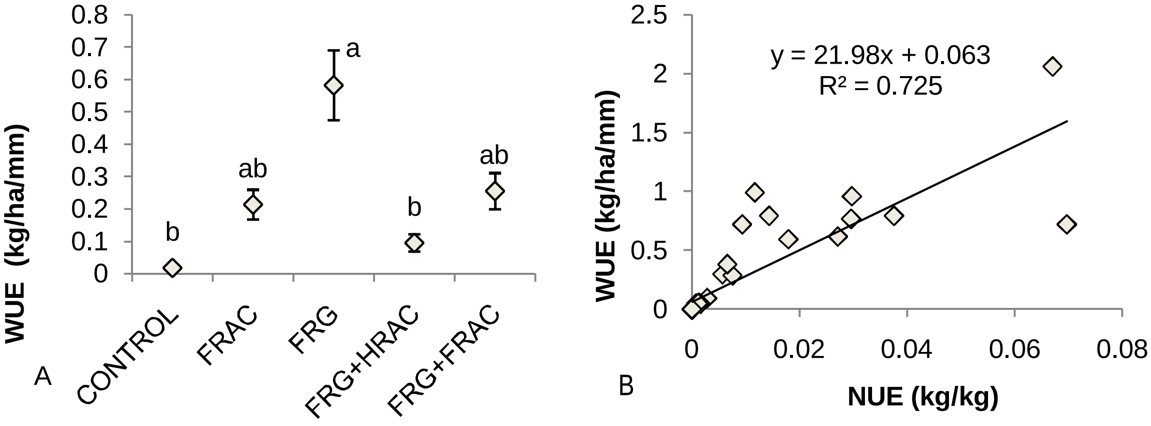


Fig. 9. Water Use Efficiency (kg/ha/mm) of common beans affected by fertility treatments (A). Error bars represent standard errors of the means. Different lower case letters on top of the bars mean significant differences between the treatment means. Relationship between water use efficiency (WUE) and nitrogen use efficiency (NUE) (B).

4. DISCUSSION

4.1 Soil organic matter and water retention

The increase in soil moisture by the full rate of glycine mix fertilizer (FRG) alone and its addition with half (FRG + HRAC) and full rates (FRG + FRAC) of compost (Fig. 1) could not be attributed to organic matter because none of these treatments on their own, affected soil organic matter (SOM) (Fig. 6). However, it is possible that the short height and spreading architecture of common beans, and the relatively large leaf number and area (Fig. 2&3) affected by nutrient supply from FRG included treatments, shaded the soil surface, reduced the reach of incident solar radiation, and reduced excessive evaporation. This confirms previous reports that using live plants as soil cover increases soil moisture by allowing more water to sink in and reducing evaporation [51]. Moreover, achieving improvement in SOM to consequently impact soil water retention usually does not occur with one application because many research findings which successfully achieved such, applied compost for two or more years [52, 53, 54]. Generally, maintaining soil moisture at 80% FC (no moisture stress) affected higher soil organic carbon and matter percentages because optimal microbial activity occurs near field capacity moisture [51], while drought stress reduces microbial activity and organic matter build-up [55].

4.2 Common bean growth, yield, nutrient uptake and residual nitrogen

Lower residual soil mineral N concentration below the initial level could be attributed to common bean N uptake to meet its physiological needs [56,57]. Already a poor biological N fixer [56, 58, 59], the supply of N from the treatments and drought imposition may have further compromised its nitrogen fixing abilities [60, 61] leading to the unexpected decline in N. However, since no significant differences were observed in N uptake by the plants and NUE affected by all treatments was extremely low, it is possible that aside plant N uptake, immobilization may have also caused the decline leading to the differences in residual N levels observed. Based on a previous compost study [62], the C:N ratio of our compost implied that, there should have been a balance between N mineralization and immobilization. However, judging from the non-corresponding increase in residual soil N above FRG, with the addition of half and full rates of compost to FRG (Fig. 7), it is evident that N was immobilized more than mineralized with the addition of compost. This is confirmed by the decline in crop growth rate (leaf number, area and chlorophyll concentration) and yield (grain yield and biomass at harvest) parameters with the addition of the compost alone or in combination with FRG relative to FRG alone (Fig. 2, 3, 4A and 5). According to a study [63], the compost applied belongs to category 3 of organic amendments (because its total N was below 2.5% but C: N ratio was below 25) which implies that it should be mixed with inorganic fertilizer for application, just as practiced in our experiment. However, studies on composting municipal solid waste compost (as used in our study) often report C:N ratios between 10 to 18 [64, 65, 66] when compost is completely decomposed. The high carbon percentage (38%) in our compost, organic matter content above 65% (calculated from C%) and C:N ratio of 23 suggest that the compost may not have been properly cured and continued decomposition after application [64, 67, 68]. In such cases, continuous decomposition leads to the loss of organic matter through microbial respiration and immobilization of N during the decomposition process [66, 67, 68]. This could have contributed to why compost addition did not improve SOM above initial levels (Fig. 6).

The generally low common bean yield in this study (highest yield was about 100 kg/ha compared to average yield of 437 kg/ha in Sub-Saharan Africa [69]) was expected because of the sensitivity of the flowering and pod initiation growth periods to drought events [35]. However, comparatively, the ready supply of relatively high levels of P and K and a starter N from FRG (NPK 5:30:30) without high N immobilization rates like compost included treatments, and the timing of its application, caused it to increase common bean growth (leaf number, area, SPAD chlorophyll) and yield (grain yield and biomass) parameters compared to other fertility treatments. Split application of FRG supplied a starter N during the temporal N deficiency stage of seedling growth when cotyledon reserves were depleted, leading to fast vegetative growth [70]. Split application of FRG at the pod development stage supplied the necessary nutrients for dry matter partitioning into pods and grain yield [71]. Common bean yield increases of up to 3600 kg/ha with the application of 0- 280 kg/ha P_2O_5 and 0-200 kg/ha K_2O even in soils with inherently high P and K levels have been reported [27]. Starter N application between 0-46 kg/ha N with *Rhizobium* inoculation has also been found to increase common bean yield by 32%, though nodulation and biological N fixation were compromised [72].

Higher K uptake by plants supplied with FRG included treatments was only an artifact of high K supply from them. Higher K uptake affected by the constant supply of 80% FC moisture compared to the water stressed plants (Fig. 8) confirms that K mobility and availability to the crops was increased by the availability of water, since soil moisture is one of the key factors controlling K availability and uptake [73]. Since soil moisture levels below 100% FC do not cause significant K leaching [74], it can be assumed that there was no or minimal K leaching in this study, hence low K uptake in water stressed plants could not be attributed to K leaching. Other authors have also reported low K uptake in common beans under severe moisture stress conditions [75].

4.3 Water and nitrogen use efficiencies

Consistent N supply from FRG and the high water retention affected by FRG, presented common bean plants with better growth conditions (nutrients and water) to produce higher biomass and yield (Fig. 5). These components translated into higher WUE for the same amounts of water supplied to all treatments. Conditions that reduce soil evaporation have been reported to also increase the WUE of crops [76]. Though NUE was generally extremely poor (Fig. 9B), the strong positive relationship between NUE and WUE confirms that better supply and use of soil nitrogen by crops could allow them to efficiently use water as well. On the reverse, there is also an intricate relationship between water and nitrogen concentration in the soil that allows crops greater access to nitrogen with adequate water supply, through transpiration driven mass flow of nutrients in the soil and uptake by roots [33]. Nitrogen affects stromal and thylakoid proteins in leaves which in turn affects the photosynthetic capacity of plants [77]. Hence, relatively higher availability of both water and N by FRG led to the higher WUE. A previous study [78] also found 35 - 45% increases in common bean yield with the application of 80,170 and 225 kg/ha N to wheat-common bean rotations under drought conditions, compared to no nitrogen application. Nitrogen immobilization affected by adding half and full rates of the compost to the fertilizer (FRG), and poor nutrient supply from the control led to poor WUE affected by these treatments.

5. CONCLUSION

This study confirms that, drought at the reproductive and pod initiation stages of common beans, has great impact and generally reduces its yield irrespective of agronomic practices implemented. However, a good supply of nutrients at the right time may offset some of the yield decline in the event of drought. Thus, the application of recommended rates of nitrogen, phosphorus and potassium at the vegetative and reproductive stages of the crop increases growth and yield components and reduces the severity of short-term droughts by improving the water use efficiency of the crop. However, research is still needed to ascertain the exact amount of N fertilizer to apply to maximize biological nitrogen fixation by common beans. Combined use of compost and fertilizer to improve common bean yield and mitigate drought effects, should seriously consider the quality of the compost because compost would not complement inorganic fertilizer to mitigate drought effects if it is not of required quality.

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AVAILABILITY OF DATA AND MATERIALS

The dataset generated and/or analyzed during the study are available from the corresponding author upon reasonable request.

COMPETING INTERESTS

Authors declare no conflicts of interests.

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