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TIED RIDGING ENHANCES SOIL WATER CONSERVATION AND PRODUCTIVITY OF COMMON BEAN (*Phaseolus vulgaris*)

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ABSTRACT

A field trial was conducted to determine the effects of different water conservation practices done in-situ on soil water content, stomatal conductance, and seed yield of common beans at Fumesua experimental station of the CSIR-Crops Research Institute in Ghana during the 2020 and 2021 cropping seasons. The water conservation practices implemented were tied ridges (TR), bunded basins (BB), and flat land (FL). Results showed that the TR treatment increased soil water content by 18 and 16% (0-5 cm), 12 and 13% (5-10 cm), and 18 and 7% (10-30 cm), compared with the FL treatment in 2020 and 2021 respectively. Across years, TR treatment increased stomatal conductance by 39 and 53% at both vegetative and flowering sampling periods. Soil water content and stomatal conductance also increased in the BB treatment compared to the FL treatment, but to a lesser extent than that of TR. The TR treatment improved seed yield by 31 and 42% over that of FL in 2020 and 2021, respectively. At a lesser magnitude, the BB treatment increased seed yield by 17 and 40% compared with the FL treatment during the same period. These results showed a positive relationship ($p < 0.05$) between the soil water content and common beans seed yield, such that an increase in soil water content determined about 75% of the increase in seed yield. Based on the results of this study, tied ridging could be considered a suitable water conservation strategy for improving common bean yield.

Key words: Water conservation, soil moisture, crop yield, water-use efficiency, seed bed management

INTRODUCTION

Agricultural production in most sub-Saharan African countries including Ghana is largely rainfed (Bjornlund *et al.,* 2020). In these countries, common bean (*Phaseolus vulgaris*) is a staple food and its production is critical for national food security (Giller *et al.,* 2021). Common bean remains a highly important crop for food and nutrition security and incomes (Yeboah *et al.,* 2021). Beans provide a key source of protein, calories, vitamins and minerals, mainly iron and zinc. An estimated 60% of the bean crop is cultivated under the risk of either intermittent or terminal drought (Smith *et al.,* 2019). Moderate to severe drought stress reduces biomass and seed yield (between 25 and 90%), number of pods and seeds, seed weight, and days to maturity (Losa *et al.,* 2022). In Ghana, climate scenarios predict a temperature rise and a change in rainfall amounts and patterns (Adeniyi and Uzoma, 2016). Higher temperatures and greater evaporation, combined with lower rainfall is expected to exacerbate drought in most legume producing areas of the country. The projected changes in climate will pose threats to legume production, food security, and subsequently to the livelihood of smallholder farmers. To reduce drought risk in common beans production, there have been calls to promote *in-situ* rainwater harvesting technologies to subsistence farmers (Oteng-Darko *et al*., 2018). Such water conservation technologies and practices work by retaining surface runoff water within the field and productive zone of the soil, thereby altering the soil water status within the root zone. Tied-ridging is one such innovative *in-situ* water management technology that can help minimize risk associated with water scarcity (Elema *et al.,* 2021) by retaining soil moisture in the productive zone of the soil.

Tied ridging is not a new technology within Ghana and the rest of sub-Saharan Africa. It involves the construction of ridges which are subsequently closed inside the adjoining furrows by earthen bunds placed at right angles to the ridges at intervals of about 2-3 m. Tied ridges have been found to result in striking yield increases for cotton, maize, cowpea, millet, and sorghum in the semi-arid tropics of Africa (Hailermarian, 2016; Galwab and Kamau, 2017; Musyimi *et al.,* 2022). Implementation of tied ridging is a low-cost soil water conservation technology (Billen and Aurbacher, 2007). Tied ridging has been effective in reducing surface runoff and increasing soil water storage in different countries as shown by the reviews by Gebreyesus *et al.* (2008) and Hailermarian (2016). As such, it could be viewed as an anti-erosion measure, and the additional attraction for this tillage method is that it can be applied easily by farmers on cropped and bare fields (Javůrek *et al.*, 2012; Hůla *et al.*, 2016; Kovář *et al.*, 2016).

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Before tied ridging can be promoted to subsistence farmers as a viable soil water conservation measure, there is the need to evaluate its likely impact on soil water status and crop physiology as well as seed yield. Elenwa and Emodi (2019) studied soil conservation practices in arable crop production among rural farmers in Omuma Local Government Area of Rivers State, Nigeria. They found that the top four priority for the adoption of soil conservation measures among farmers are to improve soil structure, protect soil from erosion and nutrient loss, reduce water usage for irrigation, and enhance water holding capacity of soils. Thus, subsistence farmers are not likely to adopt tied ridging as a soil water conservation measure unless they witness significantly, the top four identified priorities from Elenwa and Emodi (2019) in their fields. This study sought to ascertain whether tied ridges have similar effects on increasing yields in common bean production as well as its potential to reduce the vulnerability of farmers to in-season drought under rainfed common bean production. The specific objective was to identify the effect of tied ridges on soil water conservation and common bean growth and development.

MATERIALS AND METHODS

Study Site

The experiment was established in the 2020 and 2021 minor cropping seasons under rain-fed conditions at the CSIR-Crops Research Institute experimental field at Fumesua in the Ashanti Region of Ghana (6°45′00.58′ N; 1°31′51.28′ W). The soil type in the study area is classified as Ferric Acrisol, Asuansi soil series (FAO, 2014). The texture of the topsoil is sandy loam with dark brown colour (Adjei-Gyapong and Asiamah, 2002). The top 0-30 cm soil layer at the experimental site had a pH value of 4.50, 1.27% organic carbon, 0.20% total nitrogen, and 17.21% available phosphorus. Average long-term maximum and minimum temperatures span 21-32°C. Cultivation practice at the experimental site is continuous cropping under conventional tillage, involving soil inversion and smoothing operations coupled with residue removal. Field was cropped to maize (*Zea mays* L.) prior to commencement of the experiment The distribution of the seasonal rainfall during the years of the experiment was 1,134.40 mm in 2020 and 1,330.20 mm in 2021 (Figure 1).

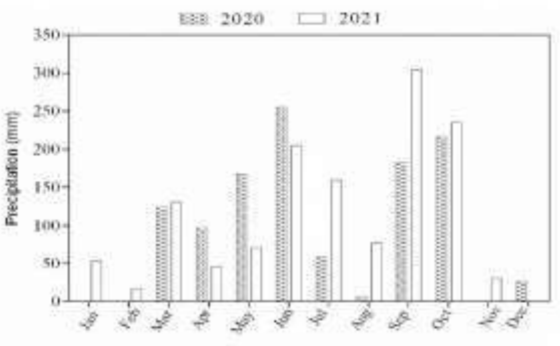


Figure 1: Monthly rainfall data for the two cropping years

Experimental Design

The experimental design used was a randomized complete block design with 3 replications (Figure 2). Common bean was planted using three seed bed options as treatments during the 2020 and 2021 cropping seasons. Seeding was done at two seeds per hill and thinned to one seed per hill, seven days after germination. The seed bed treatments were bunded basin (BB), flat land (FL) and tied ridge (TR). In the BB treatment, the crop was planted within an area with dimensions 9.00 m × 3.60 m enclosed with manually raised soils bunds of about 40 cm height on all four sides. In the FL treatment, the crop was planted within same area as the previous treatments. However, in this treatment, no bunds were raised around the area planted. In the TR treatment, the crop was planted on ridges manually formed to a height of about 40 cm within same specified area as the other treatments. Between adjacent ridges, soil was heaped to a height of about 40 cm at every 3 m to close off water runoff between the furrows from end to end. Thus, rainwater was harvested and stored within the enclosed little pans formed between the ridges. Weeds were manually controlled by weeding with hoe. The crop was produced under rainfed conditions.

Determination of Soil Bulk Density

Soil bulk density was determined by taking small cores, and by relating the oven-dried mass of soil to the volume of the core (Blake and Hartge, 1986).

Soil Water Content

Soil water content (%, w w^{-1}) at 0-5, 5-10 and 10-30 cm depth intervals was determined by taking a soil core of 5 cm in diameter, and subsequently drying the soil at 105°C until constant weight is attained. Gravimetric water content at each of the three depth intervals was multiplied by soil bulk density to obtain the volumetric water content (Obalum *et al*., 2012), which is expressed in cm^3 cm^{-3}. Soil samples for moisture content were taken from inside the plots.

Plant Height, Canopy Spread, and Stomatal Conductance

Plant height was measured from the soil surface to the tip of the main stem at the vegetative and flowering stage and expressed in cm. Canopy spread was determined by measuring the widest point and the narrowest point of the canopy. The two values were added together and divided by two to calculate the average canopy spread. stomatal conductance (gs) was measured on cloud-free days under natural light using a porometer (Model AP4, Delta-T Devices, Cambridge, UK) at vegetative (V_n: n^{th} trifoliate leaf unfolded at node) and flowering stage (R2: 50% open flowers). Measurements were conducted on middle portions of ten fully developed leaves selected from inner rows per treatment exposed to full sunlight. The data were averaged afterwards. Measurements were conducted between 09:00 and 12:00 h.

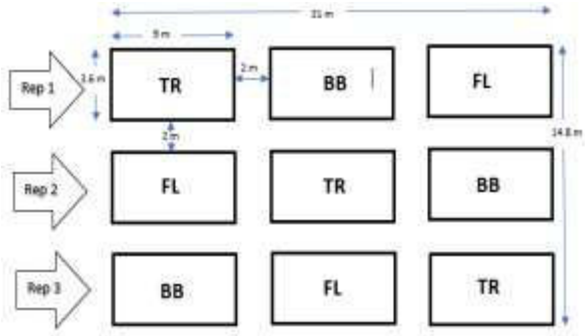


Figure 2: Illustration of the experimetal layout
TR is tied ridge; BB is bunded basin; FL is flat land

Seed Yield and Water Use Efficiency

Random sampling of ten plants on each ridge was conducted and all the pods on each plant were counted and recorded to determine the number of pods per plant. All pods from the entire net plot were harvested into perforated harvest bags, sun-dried and threshed. The seed was then weighed and seed moisture content determined using a moisture meter to extrapolate seed yield. Yields reported here are adjusted to 12% moisture content. Seed water use efficiency (WUE_g) was determined using Equation 1 described in Wang *et al.* (2014):

$$WUE_g = \frac{Y}{ET} \quad (1);$$

where WUE_g is seed water use efficiency, Y is seed yield (kg ha^{-1}), and ET is total evapotranspiration over the entire growing season (mm); ET was estimated using Equation 2:

$$ET = P - \Delta W \quad (2);$$

where ET is total evapotranspiration, P is total precipitation for the growing season, and ΔW is the difference between soil water storage at sowing and harvest. All parameters were expressed in mm.

Statistical Analysis

Statistical analyses were done with the Statistical Product Services Solution 22.0 (IBM Corporation, Chicago, IL, USA) with the treatment as the fixed effect and year as random effect. Differences between treatment means were determined using the Tukey's HSD (Honestly Significant Difference) test, with significance determined at the 5% probability level.

RESULTS

Soil Water Content

Soil water content measured during the cropping season increased with increasing soil depth, which was observed for all treatments (Figure 3). Significant differences in soil water content were only observed in some depth intervals, as shown in Figure 3. The tied ridge treatment showed consistently higher soil water contents compared to other treatments both at depth and sampling period (Figure 3). These observations were consistent in both years. Differences in soil water content between treatments were larger in the 0-5 cm depth interval. Since year had a significant effect ($p < 0.05$) on mean soil moisture in 0-5, 5-10 and 10-30 cm soil intervals, data are presented on yearly basis.

Compared to all treatments, the highest soil moisture contents were observed in response to the tied ridging, followed by the bunded basins, and the least soil moisture was observed in no flat land in all the layers studied (Figure 3). The highest soil moisture content was observed in 10-30 cm under all treatments reported here. Results showed that tied ridging increased soil water content by 18 and 16% (0-5 cm), 12 and 13% (5-10 cm), 18 and 7% (10-30 cm), compared to flat land in 2020 and 2021, respectively (Figure 3). When compared to flat land, the bunded basin had no significance in the 0-5 cm and 5-10 cm soil intervals in both years. The soil water content between tied ridging and bunded basin were statistically comparable in all the layers studied.

Canopy Spread and Plant Height

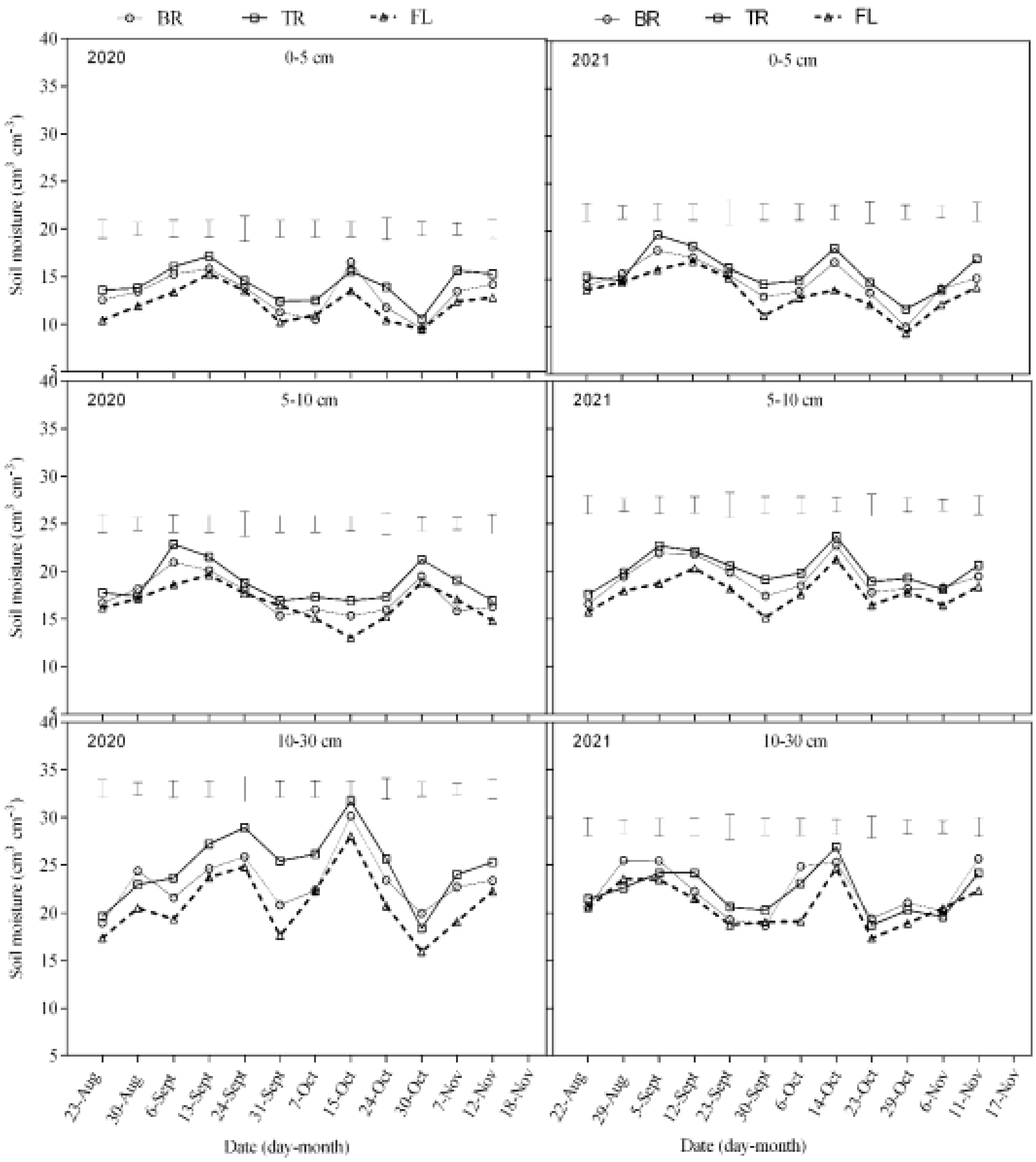
Overall, there were significant differences between treatments in canopy spread and plant height in both years. However, year had no significant effect on treatments. The tied ridges treatment increased plant height by 44 and 30% compared with flat land and bunded basin (Figure 4), respectively. The tied ridges treatment improved canopy spread by 41% compared with flatland. There was no significant difference between tied ridges and bunded basin in plant height.

Stomatal Conductance

Since year significantly affected stomatal conductance (Table 1), data are presented on yearly basis. Tied ridge treatment significantly affected stomatal conductance in both vegetative and flowering sampling periods ($p < 0.05$) compared to bunded basin and flat land. The only exception was at the flowering stage in 2021 when the differences between the TR and BB were statistically comparable. Overall, tied ridging treatment increased stomatal conductance by 39 and 53% during the vegetative and flowering sampling period. At a lesser magnitude, bunded basin increased stomatal conductance by 28 and 43% at the vegetative sampling period. Tied ridging improved stomatal conductance by 10 and 7% at vegetative stage in 2020 and 2021, respectively (Table 1).

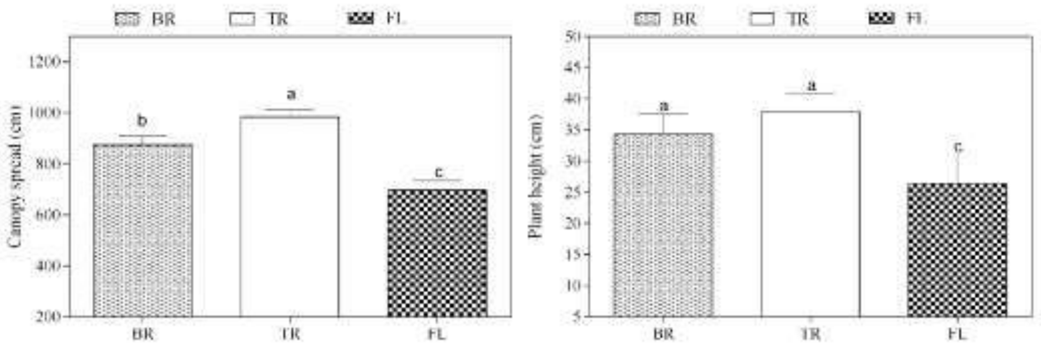
Pods per Plant and Seed Yield

In this study, the year had a significant effect ($p < 0.05$) on the number of pods per plant (Figure 5) and seed yield (Figure 6). There were significant treatment effects on the number of pods per plant and seed yield which were observed in both years. Flat land treatment decreased number of pods per plant by 58 and 51% compared with tied ridge. Similarly, bunded basin increased number of pods per plant by 52 and 39% compared with flat land. Tied ridge produced the highest seed yields both in



BB - bunded basin; TR - tied ridge; FL - flat land

Figure 3: Soil water content (%) at the 0-5 cm, 5-10 cm and 10-30 cm depth range recorded at weekly interval
Mean values (n = 3); mean comparison based on Tukey's Honestly Significant Difference test at 5% indicated with asterisk.



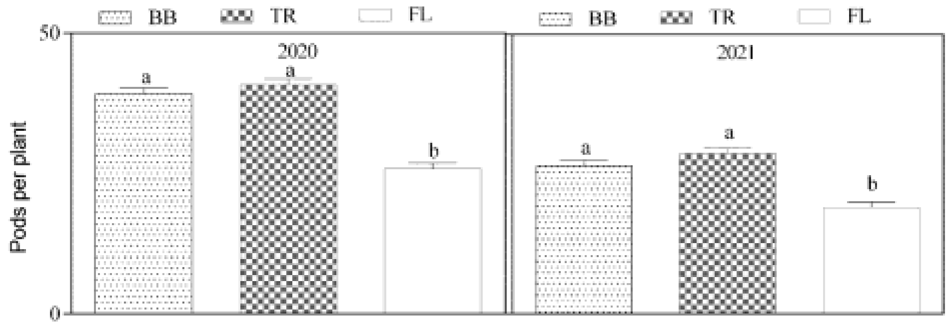
BB - bunded basin; TR - tied ridge; FL - flat land

Figure 4: Effect of treatment on canopy spread and plant height recorded at vegetative and flowering
Bars with different letters in the figure are statistically different at $p < 0.05$. Bars represent the standard error of means.

Table 1: Stomatal conductance as affected by treatments

Treatment	Vegetative		Flowering	
	2020	2021	2020	2021
BB	493.00^{b}	324.00^{b}	570.00^{b}	368.00^{ab}
TR	544.00^{a}	347.00^{a}	621.00^{a}	385.00^{a}
FL	382.00^{c}	257.00^{c}	398.00^{c}	257.00^{c}

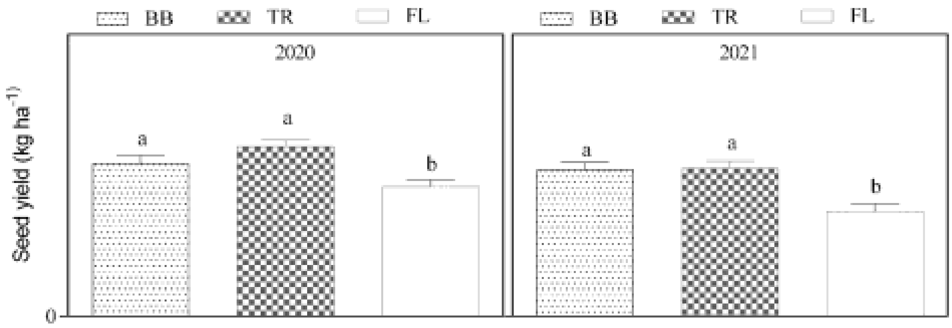
BB - bunded basin, TR - tied ridge, FL - flat land. Means in the same column with different alphabets are statistically different at $p < 0.05$.



BB - bunded basin; TR - tied ridge; FL - flat land

Figure 5: Effect of treatment on number of pods per plant

Bars with different letters in the figure are statistically different at $p < 0.05$. Bars represent the standard error of means.



BB - bunded basin; TR - tied ridge; FL - flat land

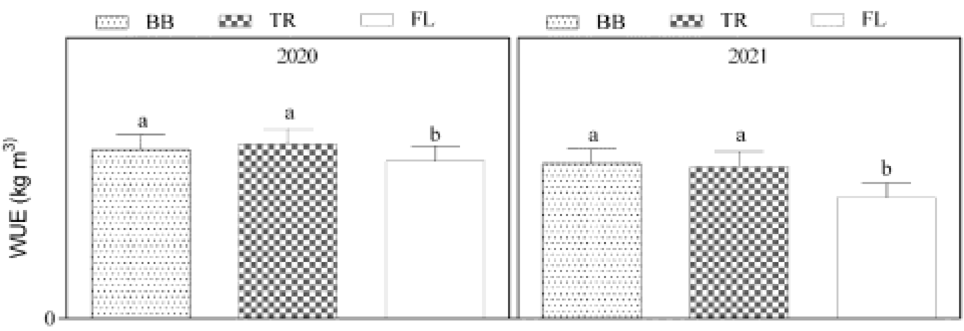
Figure 6: Effect of treatment on seed yield

Bars with different letters in the figure are statistically different at $p < 0.05$. Bars represent the standard error of means.

2020 (2,401 kg ha^{-1}) and 2021 (2,098 kg ha^{-1}). This was approximately 31 and 42% higher than that of FL treatment in 2020 and 2021, respectively. At a lesser magnitude, the BB treatment increased seed yield by 17 and 40% compared with FL treatment. The TR treatment improved seed yield by 21% relative to BB treatment, however, no significant difference was observed in 2020.

Water Use Efficiency

Results of water use efficiency (WUE) are presented in Figure 7. The TR treatment increased WUE by 12 and 27% relative to the FL treatment in 2020 and 2021, respectively. The corresponding increases due to the BB treatment were 9 and 29%, respectively. There was no significant difference between tied ridges and bunded basin in water use efficiency.



BB - bunded basin; TR - tied ridge; FL - flat land

Figure 7: Effect of treatment on water use efficiency

Bars with different letters in the figure are statistically different at $p < 0.05$. Bars represent the standard error of means.

Relationships

The regression coefficients are presented in Figure 8. Soil water content showed a significant (positive) regression with stomatal conductance ($r^2 = 0.96$; $p < 0.05$) and seed yield ($r^2 = 0.90$; $p < 0.05$). Significant regressions were also observed between water use efficiency and seed yield ($r^2 = 0.97$; $p < 0.05$).

DISCUSSION

Crop production in Ghana is predominantly rainfed, exposing this major livelihood activity to the variability or change in rainfall patterns (Kwadze *et al.,* 2013). Rainfed agriculture accounts for a large percentage of the total crop production especially rural areas in Ghana. The net potential effect of changes in rainfall patterns is the disruption in crop production leading to food insecurity, and poverty. In Ghana, increasing water productivity is an important element in improved water management for sustainable agriculture, food security and healthy ecosystem functioning. In this regard, soil water content, particularly in the 0-30 cm depth interval, is important for crop production in an environment characterized by periodic low soil moisture due to erratic and poorly distributed rainfall (Wang *et al*., 2021). Studies have shown that about 60-70% of root biomass of common beans crops grown is found within this depth (Abebe, 2017; Assefa *et al*., 2017; Samago *et al*., 2018). Therefore, increasing soil water retention at this rooting depth should also increase uptake of water and nutrients by crops leading to improved productivity. In the present study, the use of tied ridges technology was shown to increase soil water content, in the soil depth studied (i.e., 0-30 cm depth interval). This result was consistent in almost all sampling periods and years. Application of tied ridges has been reported to increase soil water content (Heluf and Yohannes, 2002; Hailermarian, 2016). It has been reported that tied ridging is beneficial for reducing runoff and soil loss, as well as for increasing crop yield (Wiyo *et al*., 2000; Mak-Mensah *et al*., 2021; Jacobs *et al*., 2022). The higher soil water content observed in the tied ridging and at least extent in bunded basin treated plots compared with flat land plots may be attributed to the potential of these technologies in reducing severe soil erosion, runoff and loss of water (Heluf, 2003). The tie acts as a barrier for the rainwater movement and increases contact time available for infiltration thus enhances availability of soil moisture to the crops (Rana, 2007; Obalum *et al*., 2011a). Increased soil water content observed within this study after application of tied ridging significantly increased canopy spread, plant height and stomatal conductance. Increased soil water content improved plant water status and the greater stomatal conductance is a strong indicator of the trends (Cramer *et al.,* 2008; Yeboah *et al*., 2017). The fact that stomatal conductance was higher in TR treatment than FL treatment provided evidence of improved water status. The lower stomatal conductance in the FL treatment could be attributed to reduced water content. Flexas *et al.* (2006) found that stomatal closure occurs as a protective mechanism against xylem cavitation due to water stress. Tillage effects on soil moisture status could differ between years (Obalum *et al*., 2012). In the present study, soil water content accounted for 96% of the variation in stomatal conductance. These results suggest that application of tied ridging technology could increase the resilience of common beans to water deficits that may occur or be induced due to high water demand. Thus, this practice offers promise to ameliorate plant water stress and improve crop performance under rainfed conditions characterized by soil erosion, runoffs and intermittent drought. Tied ridging could, therefore, be used as a reliable technique to store rainfall in soil and increase rainfall-use efficiency.

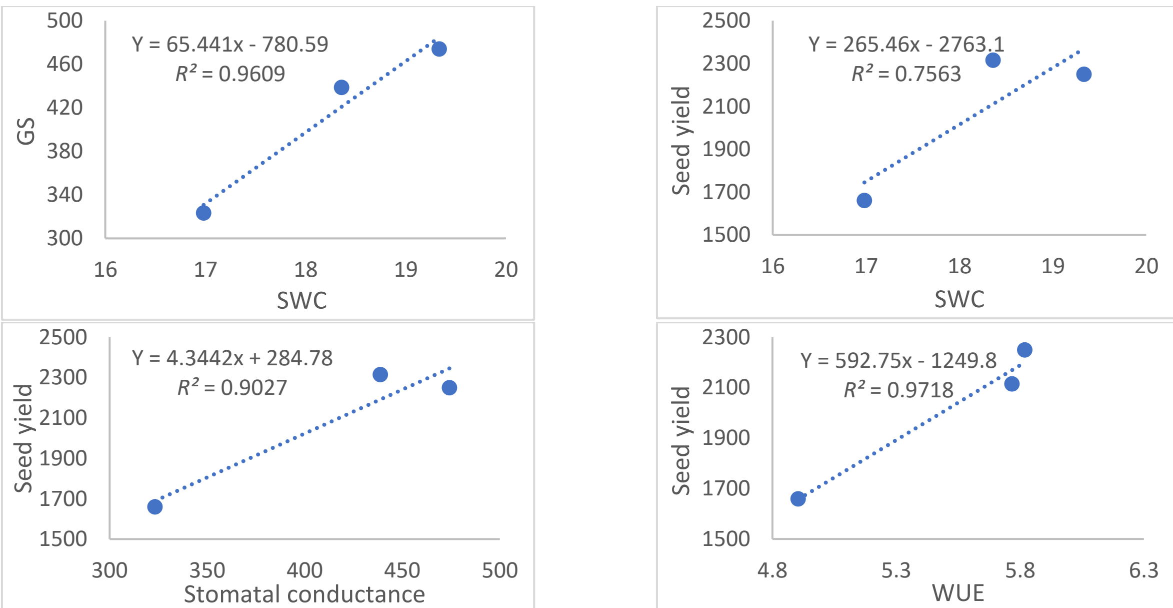


Figure 8: Relationship between the soil water content, stomatal conductance, and water use efficiency

Number of pods per plant, seed yield and WUE were significantly improved in tied ridge treatment compared to flat land in both years of the study. Field studies on tillage-based soil moisture conservation techniques have reported increases in yields and/or WUE of sorghum and soybean (Obalum *et al*., 2011b, c), and tied ridging specifically has been reported to increase the yields of improved maize and sorghum varieties by up to 37% (Solomon, 2015). Improved WUE is needed in environments where drought is a limiting factor to crop production. In this study, more than 95% of the variability in seed yield was explained by WUE; therefore, the yield benefits of tied ridging are mostly due to improvements in WUE. These yield benefits of tied ridging could be due its offering of a raised platform for enhanced availability of soil moisture during the crop growth phase when the structure of the tilled, pulverized soil was yet to fully reform (Obalum *et al*., 2017). Tied ridging is beneficial for enhancing soil enzyme and microbial activities (Ogumba *et al*., 2020), reducing runoff and soil loss as well as soil bulk density, thereby improving water retention and availability resulting in increased crop yields (Wiyo *et al*., 2000; Hailermarian, 2016; Wolka *et al*., 2018; Obalum *et al*., 2020). Severe soil erosion and runoff and loss of water and the resultant low soil fertility are the prominent causes of low agricultural productivity in Ghana (Bashagaluke *et al*., 2019; Sekyi-Annan *et al*., 2021). Seed yield correlated with soil water content and stomatal conductance; these two factors explained more than 80% of the variation in seed yield. Yeboah *et al.* (2017) reported that increased seed yield is associated with changes in stomatal conductance and soil water which also agrees with our observations. The results could also be due to the rainfall amount and distribution observed during the cropping season. Rainfall amount and distribution, inter seasonal fluctuations and erratic rainfall patterns have been reported to have resulted in reductions in crop production which has become a major issue to farmers and policymakers as threats to food security (Kurukulasuriya and Mendelsohn, 2013; Kyei-Mensah *et al*., 2019).

CONCLUSIONS

Water conservation techniques at farm level are essential options for improving yield. In this study, tied ridge was superior to bunded basin and flat land as evident in increased soil water content within the 0-30 cm depth interval which had beneficial effects on canopy spread, plant height and stomatal conductance of common bean, and this translated into the higher seed yield and water use efficiency. Improved soil water availability during the cropping season could contribute to good formation of seeds. In general, the results apparently imply that in the Ghanaian context where rainfall is increasingly characterized by low amounts, uneven distribution and erraticism during the cropping season and the soils are degraded, tied ridging is very significant.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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