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A low-cost integrated desalination and irrigation technique tested on dual-purpose sorghum in Turkana County, Kenya

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In arid and semi-arid lands, water salinity often restricts plant growth, degrades soils, and even causes irrigation systems to fail, especially in hot climates. Worldwide, it is a major cause of the irrigation-induced salinization that had already affected 76 million ha of soil in 1991. Our novel and inexpensive irrigation technique addresses these issues, thus potentially improving the food security of affected farmers and pastoralists who often are amongst the world's poorest. Saline or brackish water is dispensed inside plastic bottles that are modified so as to feed only vapour to the soil, where roots and moisture-retaining materials can capture it. We tested this method in the field in Turkana County (Kenya) with Dual-Purpose Sorghum. Five treatments in five replicates were applied with different moisture-retaining materials: biochar; organic mulch; plastic sheeting; Super Absorbent Polymer); and none (Control). Effectiveness of the treatment was appraised by comparing the average heights of plants. At 64 cm after 30 days, the Super Absorbent Polymer treatment performed best (34% better than the control, *p*=0.05), followed by organic mulch (18% better than the control, *p*=0.05). Super Absorbent Polymer and organic mulch also retained the most moisture in the soil (37 and 32% better than the control, respectively; *p*=0.05).

Key words: Irrigation, pitcher irrigation, condensation irrigation, superabsorbent polymer, mulch, salinity, brackish water, saline water, soil salinization.

INTRODUCTION

Salinity and water scarcity: their impact on crops and soils

Abiotic stresses are the major cause of crop failure, decreasing average yields for major crops by more than 50% and threatening the sustainability of the agricultural industry (Mahajan and Tuteja, 2005; Vibhuti et al., 2015a, b; Bargali and Bargali, 2016). Processes such as seed germination, seedling growth and vigor, vegetative growth, flowering and fruit set are adversely affected by high salt and water stress, ultimately causing diminished economic yield and also quality of produce (Shahi et al., 2015a, b; Awasthi et al., 2016). Salinity stress negatively impacts agricultural yield throughout the world affecting production whether it is for subsistence or economic gain (Yokoi et al., 2002; Goumi et al., 2011; Pantola et al., 2017).

This is particularly true of Arid and Semi-Arid Lands (ASAL) including many areas in Sub-Saharan Africa (SSA) where these factors limit agricultural expansion and intensification of production (Allbed and Kumar, 2013), to the point that survival of the populations who live there can remain precarious. The work presented in this paper focused on one such region, Turkana County in Kenya, whose predicament is typical of other ASAL places: a lack of food security compounded by persistent droughts. In recent years, nearly 90% of the local population has come to depend on relief food from government and aid agencies (Oduor et al., 2012). In Turkana, the mean rainfall is 200 mm/year, at about 8% of the estimated potential evaporation rate, on account of the high temperatures (Oduor et al., 2012), which exacerbates soil salinization and “capping”. Groundwater can also contribute additional salt deposition through capillary rise towards the surface (Kyei-Baffour, 2005). As a result, no more than 30% of soils are even only moderately suitable for agriculture (Turkana County Government, 2014).

Use of conventional irrigation with saline or brackish water

There is ample evidence that the use of brackish water for irrigation can degrade soils and agricultural productivity (FAO and IPTS, 2015; Qureshi et al., 2018; Wang et al., 2019). Conventional methods such as furrow and sprinkler increase salt concentrations in the root zone of the crops, and also cause seedling mortality and failed germination (Rhoades et al., 1992; Tekin et al., 2014). These conditions are most likely to occur in ASALs where there is intense evaporation, for example in Kenya, where over 40% of the land area is occupied by saline, saline-sodic and sodic soils (Wamicha et al*.,* 1986). Muya et al*.* (2010) attributed the 80% loss of agricultural productivity in the Kalacha irrigation scheme between 1984 and 2005 to increased soil salinity over that period, which was exacerbated by high temperature and relatively high wind speed. The interactions between water and soil salinity can also be complex, with dissolution or deposition taking place between the two, depending on the respective salinities of the two environments (Krishan, 2019), including leaching of salts in soil into aquifers (Krishan et al., 2020) and re-deposition in the topsoil when irrigating with groundwater.

High salinity can also disable irrigation systems when salt crystals block emitters (Pachpute, 2010). One of the authors observed that blocked emitters and filters on one of the irrigation projects in Napuu (Kenya) had caused some discouraged farmers to abandon their plots. Modern irrigation technologies that overcome salinity exist, for example electro-dialysis and multi-stage flash (Mezher et al., 2011), but their high costs are beyond the reach of poor farmers.

In Turkana, deployment of irrigated agriculture has been through drip, basin, furrow and sprinkler irrigation methods, all of which are being limited by high salinity levels and scarcity of fresh water. Spate irrigation within sand beds has been increasingly developed, but only provides relief for a few weeks after each rainy season (Oxfam, 2018).

As an alternative to conventional irrigation, pitcher irrigation is a relatively cheap traditional technique that uses unglazed earthen containers partially sunk into the ground that release water slowly to the surrounding soil (Bhatt et al*.,* 2013). This method is not in use in Turkana (Oxfam, 2018), in spite of being able to achieve significant water efficiency through a self-regulating mechanism where moisture gradients induced by plant consumption drive the seepage of water from the pitcher. However, pitchers do not retain salinity, and with saline water pitcher, irrigation may create irregular accumulation of salts in the soil. In field tests, solutes spread downwards, upwards and sideways from the pitcher due to capillarity and surface evaporation, and salts accumulate near the surface of the soil and on the outer sides of the soil mass that has been wetted by the pitcher (Keikha and Fatemehkarandish, 2015; Naik et al., 2008: Siyal et al., 2007; Alemi, 1980). Siyal et al. (2007) suggested remediating this by a heavy dose of flood irrigation at the end of crop production, but in the long run this technique may not prevent soil salinization in areas of high evapotranspiration, and it also uses large amounts of scarce water.

Vapour-fed irrigation with pitchers

To address this issue, we adapted a little known technique, condensation irrigation, in which a solar still

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evaporates saline water and feeds the resulting vapour and its condensate to the root zone of plants through distribution pipes (Lindblom and Nordell, 2006; Yousefi et al., 2017). This approach would present challenges with scaling-up the stills and the piping, in particular the efficient and equal distribution of limited amount of vapour to all the plants. In order to reduce complexity, risks and costs, our decentralized approach relies on modified pitchers where the evaporation takes place. It can be assisted by adding moisture-retaining materials to the soil.

This novel “vapour-fed” pitcher technique invented by co-author Dimitri Mignard uses pitchers that are impervious to water, but with holes near the top, still at root level but above the level of water. The holes need protection against ingress from soil particulates e.g. using a layer of textile. The textile must let the water vapour (or the water that has condensed on the internal surface near the top of the bottle) escape through the hole and into the soil. The evaporation is powered by heat provided by the soil as well as direct insolation of the top of the pitcher. The moisture-retaining material captures the water (be it in vapour or condensed form) before it can escape.

In this study, we made our pitchers from large (20 L), transparent plastic bottles which are readily available and are easy to modify for this purpose. Keeping the neck and shoulder of the bottle above ground allows direct solar radiation to be trapped, thus enhancing the evaporation rate within. In this way, we integrate desalination and irrigation within a simple and affordable device. The retention of moisture should also help with recovering degraded soils or preserving them from degradation. The system is illustrated in Figure 1.

Amongst the possible moisture-retaining materials that could be used to compliment the proposed method in view of their demonstrated performance in the field, the following are available:

i) SuperAbsorbent Polymers (SAP) (Shahid et al., 2012; Ahmed, 2015; Nnadi and Brave, 2001; Yangyuoru et al., 2006; Yang et al., 2014; Bai et al., 2010).
ii) Biochar (Ali et al., 2017; Li et al., 2018; Mašek et al., 2018; She et al., 2018; Langeroodi et al., 2019; Yang et al., 2020).
iii) Organic mulch (Jabran, 2019; Larney and Angers, 2012).
iv) Plastic sheeting, also known as inorganic mulching (Ahirwar et al., 2019; Kasirajan and Ngouajio, 2012).

Aims and research hypotheses of this study

This study aimed at establishing a proof of concept for the novel vapour-fed pitcher irrigation technique presented earlier, while exploring the applicability of the technique to the cultivation of dual-purpose sorghum in Turkana County.

Specifically, the objectives were to:

i) Compare the growth of dual-purpose sorghum with this method for five soil treatments that use different moisture-retaining materials: biochar, SAP, organic mulch, plastic sheet cover, and none (control).
ii) Compare the soil moisture, electrical conductivity and pH of soil during dual-purpose sorghum cultivation using this method, for the five different treatments that were listed above.

The research hypotheses that were tested were the following:

1. A crop of dual purpose sorghum can be grown by using this method.
2. The method does not entail a deterioration of salinity or pH in the soil.
3. The growth of the crop is improved by using moisture-retaining materials.

Significance of the study

The technique under investigation in this study could potentially help to support farmers and pastoralists that depend on brackish or saline water for irrigating their crops. This technique could save these people precious time and money that they must spend paying for fresh water or fetching it from distant sources. As a minimum, the technique might help crop survival during droughts. Depending on the labour that would be involved, it may also free women and children for economic activity or learning, since the burden of fetching fresh water usually falls on them. Additionally, farmers would be able to adopt the most suitable combinations of soil moisture retention materials. This approach should protect and enhance soil health and crop productivity, and hence reduce the food insecurity in the region. The results are expected to have wide applicability within ASALs that have a hot climate.

MATERIALS AND METHODS

Study sites and their respective soil and water quality

The project research sites were St. Teresa Pastoral Centre (coordinates 3.113° N, 35.590° E) and Bishop Mahon Primary School (3.125° N, 35.588° E) (aerial views for both are shown in the Supplementary Information), both in Lodwar (the County capital of Turkana). The area is semi-arid, receiving approximately 200 mm of rainfall in a year (NOAA, 2015; Olang, 2000), half of which

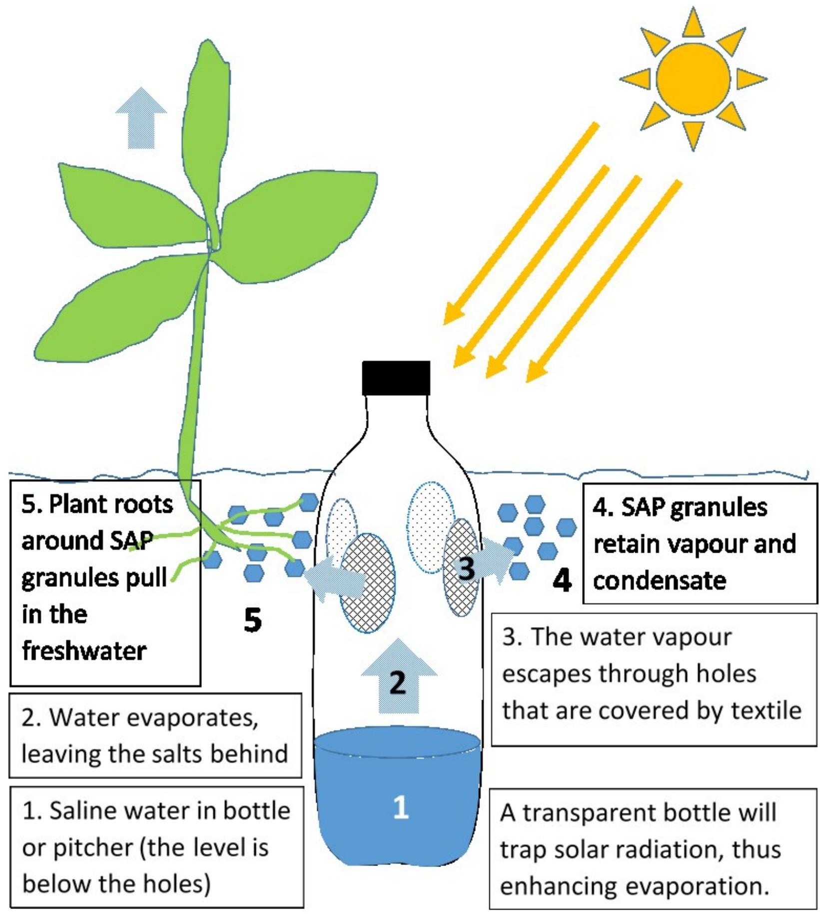

Figure 1. Proposed integrated irrigation and desalination by humidity absorption using SAPs.

occurs from March to May. The average temperature through the year is 29.6°C with night temperatures at 26.9°C and day temperatures at 32.3°C (NOAA, 2015, data averaged over 2011 – 2015). Most vegetation is of acacia bush. The soils are generally sandy-loams, poor in organic matter, shallow, rocky and stony. Pretrial analysis of the water and soil taken from the sites were carried out in KALRO Laboratories in Nairobi as presented in detail in the Supplementary Information.

St Teresa's Pastoral Centre Farm lies within the estuarine zone of River Turkwell, whose intrusion waters dilute the salts in soil. The water there had a near neutral pH (6.86), a medium salinity level (Ec = 0.27 mS/cm) and moderate Sodium Adsorption Ratio (0.38), suitable for irrigation for plants with moderate salt tolerance (e.g. maize, tomatoes, vegetables, etc.). The soil was not saline (Ec = 0.4 mS/cm) but with pH at 7.9 on the boundary between slightly and moderately alkaline (USDA, 2002). It had low soil organic carbon and deficient nitrogen and phosphorus (Supplementary Information).

On the Bishop Mahon site, the water had an excessively high pH (8.92) and high salinity level too (Ec = 4.70 mS/cm), which made it unsuitable for irrigation purposes (the high SAR at 52.1 also indicating that infiltration of water could become compromised). The soil was slightly saline (Ec = 7.11 mS/cm) and moderately alkaline (pH = 8.2). It had low soil organic carbon and a deficiency in nitrogen, phosphorus, zinc and copper (Supplementary Information).

Choice of crop: Dual-purpose sorghum

This study required a suitable crop for the environment and populations of Turkana. The major source of livelihood in ASALs, including Turkana, is livestock, but pastoralists are increasingly receptive to crop production such as dual-purpose cow peas and horticultural crops (onions, tomatoes, melons) as a remedy to the continuous reduction in natural pastures (CTA, 2014). We selected dual-purpose sorghum because it was selectively bred to help pastoralists adopt crop farming as it can also be used as fodder and for silage (Mwangi et al., 2017). It can overcome dry spell conditions and resume growth when sufficient moisture becomes available. It is also tolerant to salt, with some varieties able to produce grain when fed water of salinity up to 8 mS/cm (Devi et al., 2018).

Variety BJ28 was chosen as the test crop in this study, produced by Kenya Agriculture and Livestock Research Organization in Lanet. Its maturity period is only 110 days, its final plant height is 1 m and its grain yield is 3 t/ha (compared with 1.2 t/ha for the local varieties). The dry matter content (14 t/ha) also has 10% more digestibility in livestock than the local varieties (Gachuki et al., 2016). Other advantageous features are its ability to ratoon after harvesting, its brown grain (less attractive to birds), and that it can be intercropped with beans, cow peas, soya beans and *Leucaena* species.

Experimental treatments

Experimental treatments were biochar (B), manure (M), inorganic mulch cover (I), organic mulch (O), SAPs (S) and a control without treatment (C). All of the treatments comprised a modified pitcher at the centre of a Zai pit that fed only vapour to the crop.

The Biochar (B) was prepared with *Prosopis juliflora* (an invasive, abundant and widespread shrub species in Turkana) in a metallic kiln made by KEFRI in Lodwar, and applied at a rate of 20 ton/ha (that is, 4.5 kg per Zai pit).

The organic mulch cover (M) was made with locally available dry banana leaves, chopped into ca. 50 mm small cuttings spread thinly at an average depth of 50 mm on the soil surface over the entire area of each zai pit (except for the pitcher and foliage).

The Inorganic mulch cover (P) was a silvery plastic sheet (30 μm gauge) supplied by Post Modern Farms Ltd (Kenya), chosen for reflecting away the high solar radiation; thus, also lowering the soil temperature at the root zone. It covered the entire area of the Zai pit except for the pitcher and the crops.

The Super Absorbent Polymer (S) granules (Na, K, polyacrylate) were supplied by Belsap Ltd (Kenya). The SAPs were placed adjacent to the holes in the upper part of the plastic bottles about 30 mm below the soil surface. The chosen application rate was 3 g per plant, consistent with the manufacturer's recommendations.

The Control (C) sites had no moisture-retaining material added into (or over) the soil. This practice could also be of practical interest as a minimal cost farming practice.

Experimental layout and replication through completely randomized design

On each site, a 15 m x 12 m open drip irrigation field system was established with a 1000 L water capacity plastic tank raised at a metallic platform of 1.5 m high. The main water supply was connected from a nearby borehole with brackish water. The field was divided into five rows of five Zai pits where the crops were planted. Each Zai pit had a square surface area of 1.5 x 1.5 m, in the middle of which a modified pitcher was placed as illustrated in Figure 1. Polyethylene mains and sub-main pipes for the drip irrigation were used (diameter 32 mm and 25 mm, respectively). LDPE laterals (diameter 16 mm) were laid in the rows of the crop, emitting water inside each one of the pitcher bottles through button drippers at an adjustable rate of up to 4 L/h at predetermined volumes and scheduled times. Button emitters were selected as being less prone to blockage by salt deposit and allowing easy flushing.

On each site, the five treatments were distributed between the Zai pits in a completely randomized design (CRD) with five replications for each. The study parameters were: crop height; soil moisture; pH; and electrical conductivity of the soil.

Modified pitchers

The modified pitchers were made of 20 L transparent HDPE water bottles (diameter 28 cm, height 46 cm including neck.) These were single-use plastic bottles originally for drinking water, into which 19 mm diameter circular perforations (Figure 2) were made as follows:

i) Height of the centre line of all perforations: 26 cm from the bottom of the bottle.
ii) Three sets of three, each set symmetrically at 120° around the bottle. Within each set, the perforations are spaced level around the bottle at 25 mm.

The bottles were buried at 29 cm from the bottle base. Moisture retaining materials for treatments (B) and (S) were applied at 3 cm below the surface and covered with topsoil. Figures 2a and 2b show the perforating of the bottles and the application of the textile.

Study site preparation (Zai pits establishment)

The experiment was conducted during a continuous period when there was no rainfall, so as to clearly establish the contribution of water vapour to plant growth. However, in practice the techniques that we are testing would take advantage of rainfall water that would remain trapped in the Zai pits close to crop roots (Ahmed, 2015). During preparation of the Zai pits, the topsoil and the sub-soil were separated. Thereafter, the topsoil was mixed with well decomposed farmyard manure from a nearby goat farm in the ratio of 1:1 and returned to the Zai pits, leaving a micro-catchment. The extensive preparation and mixing of ingredients required for the Zai pits also ensured that within any one of the two sites there would be uniformity of structure and contents in the soil across all of the pits. The chosen depth of 1 m allowed a plastic pitcher bottle to be placed about 0.5 m from the Zai pit base, hence leaving another 0.5 m of Zai pit depth to contain the micro basin. The bottle lids were flush with normal ground level so as to supply drip irrigation laterals evenly. To minimise vapour losses around the lid, an in-built 16-mm HDPE pipe portion was driven down through the lid and connected to the adjustable button drippers on the inside. Plasticine was forced in the gap around the tube where it penetrated the firmly closed lid, in order to minimize the loss of water vapor through that route.

Treatments establishment

Each pitcher was then filled to ½ its full capacity with the saline water, following which dual purpose fodder sorghum seeds were planted at three points per opening around the pitcher at 2.5 cm away from the pitcher.

Irrigation amount and frequency

During the first 10 days after the initial planting (from 26th January to 4th February, 2019), water was applied directly to the crop in order to allow its germination and establishment and there was no vapour-fed irrigation. With a button dripper discharge rate set at 4 L per hour, application twice per day for ten minutes dispensed 1.3 L of water per day to each zai pit (nine plants), hence a total consumption of water of 325 L per site over 10 days.

During the rest of the experiment, only vapour-fed irrigation was applied (Anticipated harvest time had been on the 90th day, but this was cut short by a locust attack on the 62nd day). The bottles were inspected daily to check their level, then refilled to a level slightly below that of the holes. Care was taken to ensure that the water level would not reach the holes, thus avoiding direct contact with the soil. There likely was no precipitation during the period over which the experiment ran (January 26 to March 30, 2019), according to the NOAA 's records for the Lodwar weather station (the "Relative Humidity Summary: Frequency of Occurrence" showed that the hourly average of relative humidity was never

Figure 2a. Perforating a bottle with a hot metallic rod (Left); b) Strapping polyester textile around a bottle (right).

above 80% during this period)

The actual water consumption (which could have been measured by the daily drop of water level in the bottles after refill) was not monitored in these trials. Instead, the operators were instructed to take special care when refilling the bottles that they avoided letting the level of the water reach the textile band that covered the holes.

Phenological measurements and other data measured in the field

The parameters that were measured include plant height, soil electrical conductivity, soil moisture content and soil pH. For each plot, three sorghum plants were randomly selected, tagged and monitored for height. Their heights were obtained using a tape measure. Measurements were taken from the highest photosynthetic tissue to the ground level (Cornelissen et al*.,* 2003). Plant height was determined after every week after establishment for 8 weeks.

Soil temperatures, pH and electrical conductivity of the saturation extract (ECe) at a depth of 15 and 10 cm from the pitcher wall were also determined in the field using a hydroprobe and EC-TDS meter respectively. Soil moisture (in volumetric %) at the same distance from the pitcher and depth was measured from a soil sample that was collected and analysed in the laboratory following the same method as in the pre-trial analysis of soils on each of the sites, that is, by gravimetric measurements before and after drying in an oven (more detail can be found in the Supplementary Information). These tests were taken weekly in the field.

Data analysis

For each plot, an ANOVA was applied to the mean values of plant height, soil pH, soil electrical conductivity and soil volumetric moisture content that were obtained on the 10th, 17th, 23rd and 30th Day after planting (DAP), to determine the statistical significance of the treatment effects on each of these variables averaged over the duration of the experiment.

If ANOVA results pointed to differences of effects between treatments, this was followed by a Duncan's Multiple Range Test to compare the treatment means and to determine the significance of differences in these means (that is, the likelihood that these differences were not the result of chance occurrence) at $p = 0.05$.

To appraise whether significant changes in soil salinity occurred during the experiment, we compared mean values for each treatment between the first and the last day when measurements were taken for both sites, and conducted a simple 95% confidence interval test where no overlap indicated a 95% likelihood that salinity had changed during the course of the experiment.

RESULTS

Soil salinity

Figure 3 tracks the soil conductivity for the two sites with a box and whisker diagram showing the spread of results between replicate plots (the extremities indicate minimum and maximum values, crosses the mean values, and boxes 2nd and 3rd quartiles). The salinity differences between the two sites persisted even after the preparation of the zai pits had improved the soil. With an EC at around 4 mS/cm, the soil at the Bishop Mahon still just qualifies to be classified as saline, whereas the soil at St Teresa remained below that limit (0.4 - 1.2 mS/cm). The plants on the Bishop Mahon site may have been destroyed by animals shortly before the 30th day after

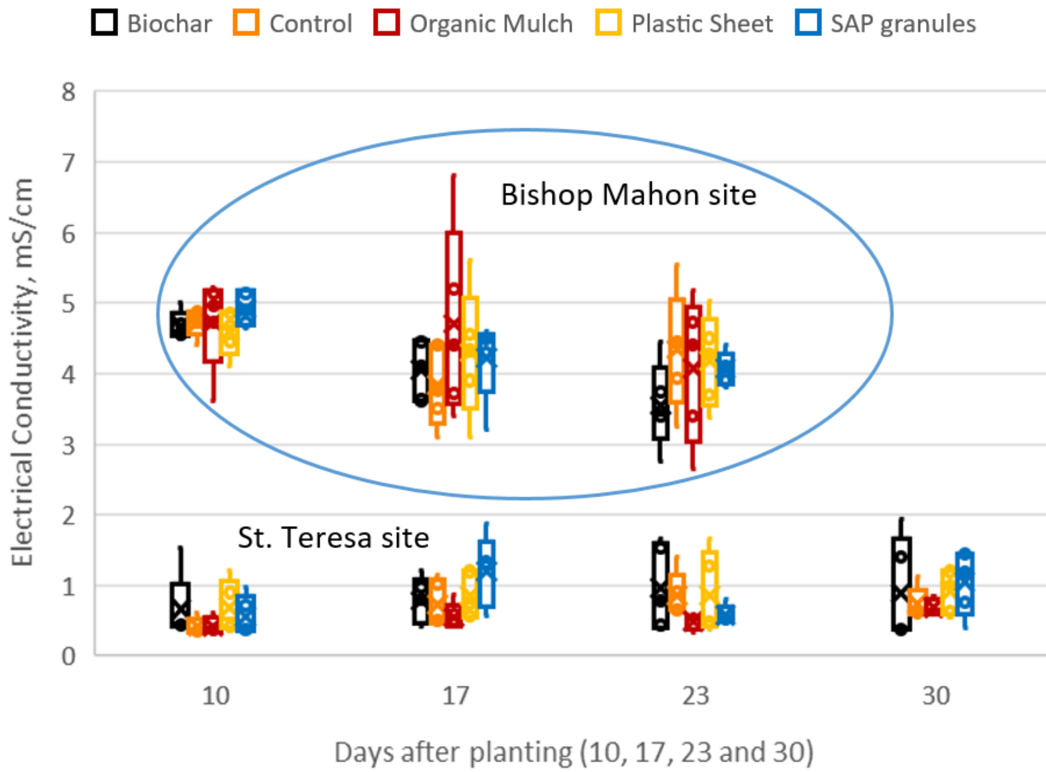

Figure 3. Soil salinity at the Bishop Mahon site and at the St Teresa site (with box and whisker representation of the five replicates plots for each treatment).

planting.

The ANOVA results for Bishop Mahon indicated that there was no significant influence of treatment on EC (p = 0.56). However, the analysis also demonstrated that EC significantly changed through the duration of the experiment (p = 0.002), with the average value across all plots dropping from 4.73 mS/cm on day 10 to 4.04 mS/cm on day 23 after planting.

Figure 4 compares the mean salinities between the 10^{th} and 23^{rd} day on the Bishop Mahon site for each treatment, with the 95% confidence interval for each. Mean salinity decreased for all treatments, with the decrease being significant for biochar and for SAP (p = 0.05).

The ANOVA results for St Teresa indicated that there might be some influence of treatment on EC (p = 0.06) (Although this is just short of p = 0.05, it may just be that more replicates would have cleared the threshold for 95% confidence). However, the analysis also demonstrated that EC significantly changed through the duration of the experiment (p = 0.03), with the average value across all plots increasing from 0.55 mS/cm on day 10 to 0.86 mS/cm on day 30 after planting.

Figure 5 compares the mean salinities between the 10^{th} and 30^{th} day on the St Theresa's site for each treatment, with the 95% confidence interval for each. Mean salinity increased for all treatments, with the increases being significant for the control and the organic mulch treatments (p = 0.05).

Other differences between the two sites

Table 1 reports the average height, moisture content and pH for the two sites, averaged over the first 23 days after planting, which was the last day of the experiment for which data were available for comparison between the two sites of this study. Stark differences between the two sites are apparent even without statistical analysis for the means of plant heights. At the Bishop Mahon site, these ranged from 9.10 to 12.1 cm, whereas they ranged from 20.3 to 30.2 cm at St. Teresa, that is, at least twice as much.

All in all, the span of moisture contents was fairly narrow (17 – 23%) across all treatments and sites. At the Bishop Mahon site, SAPs and organic mulch performed best (21.0% and 19.4%, respectively). Control retained the least moisture (17.1%). These trends were repeated at the St. Teresa site.

Results on the pH showed little, if any difference

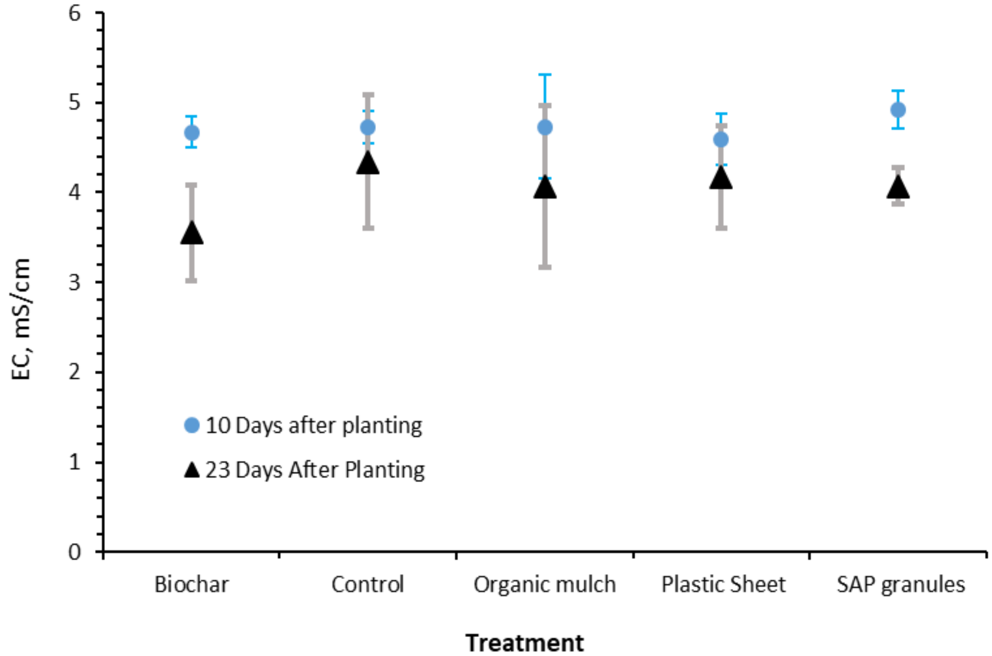

Figure 4. Comparison of mean soil salinity at the Bishop Mahon site between 10 days after planting and 23 days after planting, for each of the treatment. The error bars correspond to the 95% confidence intervals calculated from measurements for the five replicates plots for each treatment.

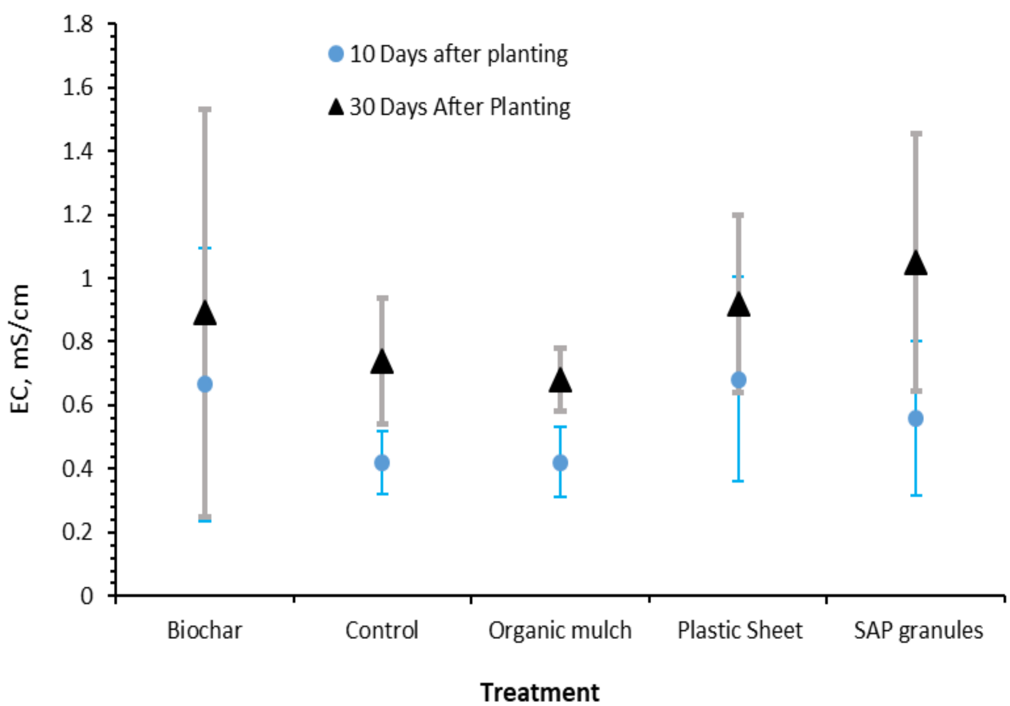

Figure 5. Comparison of mean soil salinity at the St Theresa site between 10 days after planting and 30 days after planting, for each of the treatment. The error bars correspond to the 95% confidence intervals calculated from measurements for the five replicates plots for each treatment.

Table 1. Means at the two sites averaged over the first 23 days after planting.

Treatment	Bishop Mahon			St. Teresa		
	Height (cm)	Moisture content (Vol. %)	pH	Height (cm)	Moisture content (Vol. %)	pH
Biochar	11.52	19.3	8.2	23.43	20.1	8.1
Control	9.99	17.1	8.1	20.33	17.4	8.1
Organic mulch	11.52	19.4	8.1	25.68	22.4	8.2
Plastic sheeting	11.07	18.6	8.2	23.79	20.0	8.0
SAPs	12.12	21.0	8.1	30.18	23.3	8.1

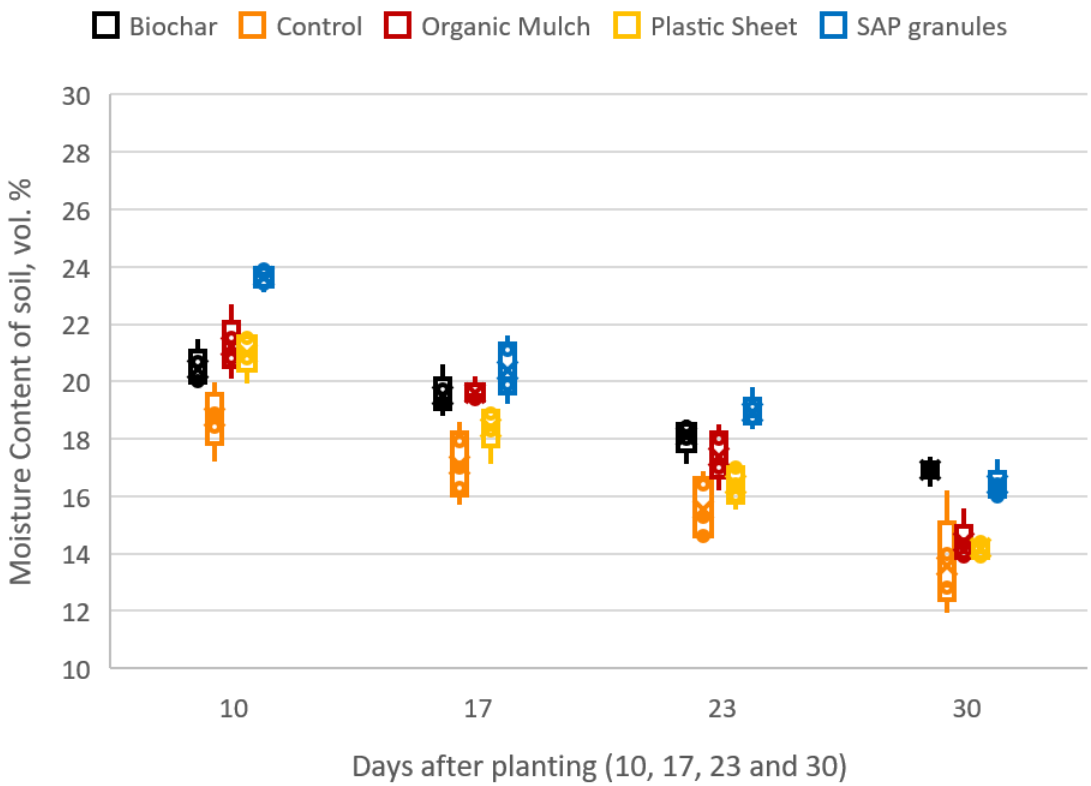

Figure 6. Soil moisture levels at the Bishop Mahon site during the experiment.

between sites and between treatments (ranging within 8.1 - 8.2 at Bishop Mahon, and 8.0 - 8.2 at St Teresa).

Evolution of soil moisture during the experiment

When plotting the evolution of soil moisture content during the experiment, it can be seen that soil moisture at the Bishop Mahon site declined by about 4 - 7% point (Figure 6) for all treatments, and by similar amounts at the St Teresa site (Figure 7).

For both sites, the ANOVA confirmed that there were significant effects associated with treatment ($p < 0.001$) and also with time elapsed since planting ($p < 0.001$).

Duncan's Multiple Range Test over the 30 days of the experiment confirmed what seemed apparent on Figure 6. The SAP treatment was associated with a higher mean level of moisture at the 5% significance level (20% at Bishop Mahon and 22% vol. at St. Teresa) when compared with the next 'best' treatment (Biochar at Bishop Mahon, 19% vol.; and Organic Mulch at St Teresa, 21% vol.). The control, where no additional moisture-retaining treatment was applied, corresponded to the driest environment (16% at both sites), lower than all the other treatments (p = 0.05). Table 2 summarizes the results from the test for the St Teresa's site.

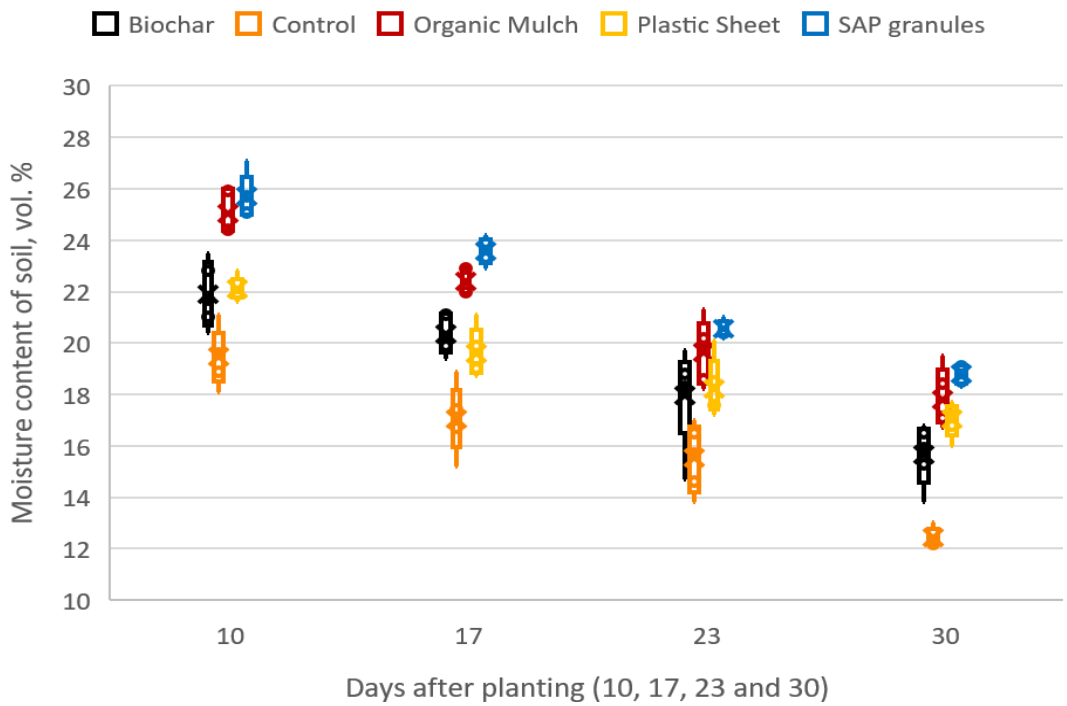

Figure 7. Soil moisture levels at the St Teresa site during the experiment.

Table 2. Significant intervals from the Duncan' s Multiple Range Test on the moisture data over 30 days at the St Teresa's site.

Treatment	Soil moisture content (vol. %)	Significant range
SAP	22.2	a
Organic mulch	21.2	b
Biochar	19.2	c
Plastic sheeting	19	c
Control	16.1	d

A similar conclusion applied to the Bishop Mahon site. In summary, compared with the control:

i) At the St Teresa site, the SAP treatment retained 37% more moisture than the Control (p = 0.05), the Organic Mulch 32% (p=0.05), the Biochar and Plastic Sheeting 19 and 18% respectively (p=0.05, though the difference between the two was not at that level of significance).
ii) At the Bishop Mahon site, the SAP treatment retained 22% more moisture than the Control, the Biochar 15%, the Organic Mulch 12%,and the Plastic Sheeting 8% (differences between each of the treatments at p = 0.05). Hence the order of performance was slightly different than from what was observed at the St Teresa's site, with Biochar taking the place of Organic Mulch. However, SAP remained the best performing material, Control remained the least performing and Plastic Sheeting remained next from last.

Evolution of plant heights during the experiment

Figures 8 and 9 below chart the changes in plant heights for both sites. They confirm that the plants at Bishop Mahon performed less well than those at St Teresa, including during the establishment period in the first 10 days. Their heights were below 6 cm on day 10, compared with 8 - 13 cm at St Teresa, to the extent that for the control and organic mulch treatments a reduction in the mean height was observed between the 17th and 23rd day.

In Figure 9, it can be seen that the mean heights reached by the plants on day 30 ranged between 44 and 55 cm depending on treatment. It should be noted that

Table 3. Significant intervals from Duncan's Multiple Range Test for mean height at St Teresa.

Treatment	Mean height over 30 days (cm)	Confidence range
SAP	36.63	a
Organic mulch	31.76	b
Biochar	29.82	bc
Plastic sheeting	28.89	bc
Control	27.02	c

one of the five plots for the organic mulch treatment was lost between day 23 and day 30, destroyed by wildlife or rogue livestock.

The ANOVA applied to plant heights at the Bishop Mahon site over the 23 days of the experiment failed to evidence any significant effect on height of any of the treatments (p = 0.60), though there was still some significant growth of the crop across all treatments (p < 0.001).

At the St Teresa's site, the effect of treatment during the 30 days of the experiment was significant well within the 95% confidence interval (p < 0.001), and likewise for growth over time (p < 0.001).

Regarding the respective effectiveness of individual treatments at the St Teresa's site, a Duncan's Multiple Range Test over the 30 days of the experiment gave the results shown in Table 3.

Table 3 shows that the SAP treatment performed significantly better than all the others. In summary, compared with the control:

1. For the St Teresa site, at 36.6 cm mean height over 30 days, the SAP treatment performed 15% better than the next best performing treatment (which was organic mulch, 31.8 cm) (p = 0.05), and 36% better than the control (p = 0.05). The organic mulch came second at 31.8 cm, 18% better than the control (p = 0.05). The Biochar and the Plastic Sheeting treatment performed 10 and 7% better than the Control, respectively; however, these differences were not within the 5% significance level when comparing them between each other, and between themselves and the control, and also between themselves and the organic mulch treatment.

ii) For the Bishop Mahon, there was no significant effect for any of the treatments.

Relevance to pastoralist communities and other stakeholders

The flowering sorghum (Figure 10) was shown to students at Bishop Mahon School as well as pastoralists during community training workshops delivered by two of the authors, Jesse Owino and Fabian Kaburu, including 58 days after crop planting, that is, 28 days after the last measurements, when the picture shown on Figure 8 was taken. Reactions from the community was encouraging as pastoralists expressed their excitement at the short time taken to produce, which particularly suits their needs since they must be moving their herds from one grazing place to another throughout the year to keep them fed.

DISCUSSION

Salinity

The growth of sorghum was not as successful at the Bishop Mahon site as it was at the St Teresa's site, as noted earlier when inspecting Table 1 and Figures 8 and 9. This disparity may be explained by the difference in water and soil salinity between the two sites. Firstly, the salinity of the borehole water at Bishop Mahon may have impacted on the germination and initial growth of the seedlings during the establishment period (Awasthi et al., 2016; Goumi et al., 2011; Shahi et al., 2015a; Vibhuti et al., 2015b), when the water was used directly to soak the seeds without prior evaporation through the bottles. Combined with the more markedly saline character of the soil, as noted earlier when describing Figures 3, the growing conditions at Bishop Mahon would be less favourable than those at St Teresa.

Salinity evolved significantly during the growth of sorghum on both sites, with an increase for all treatments that was within p = 0.05 or close to that figure for some of the treatments in the case of St Teresa, but a decrease of all treatments that is also within p = 0.05 for some of the treatments at the Bishop Mahon site.

This different direction of change of salinity at the two sites could be explained by the use of direct watering in the germination and initial establishment of the seedlings during the first 10 days. An overall increase or decrease in salinity would depend on the balance between rate of dissolution and leaching down of the water, on one hand (rates which will increase with concentration gradients between soil and water), and capillary rise and evaporation (or evapotranspiration) on the other hand (Krishan, 2019; Krishan et al., 2020). Thus, in the saline

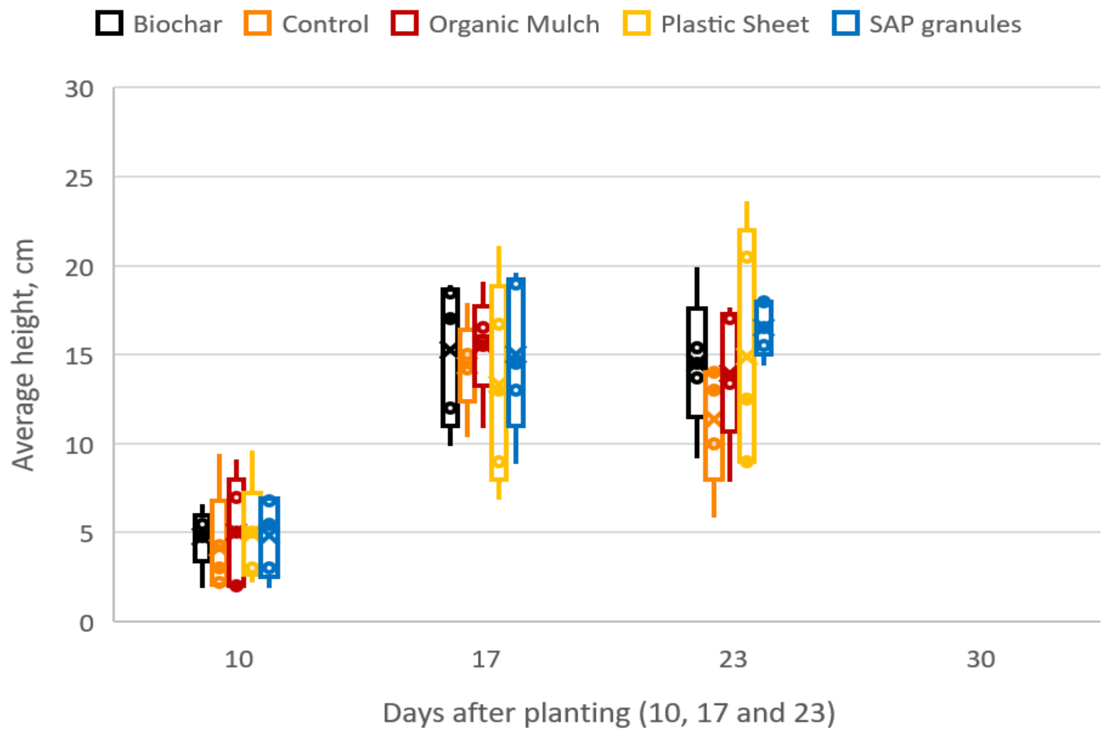

Figure 8. Plant height at Bishop Mahon site.

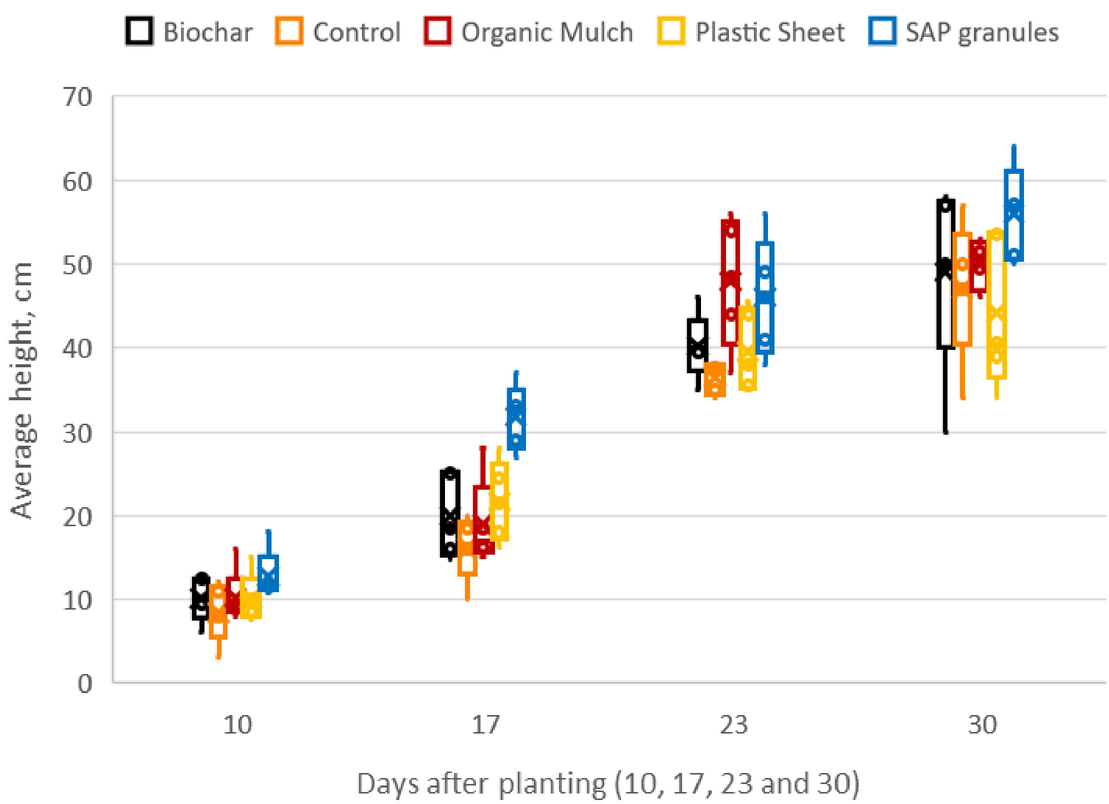

Figure 9. Plant height at St Teresa site.

Figure 10. Community training at St Theresa on March 27th 2019, 58 days after planting, that is, 28 days after the last measurements were taken. Further data collection had been arranged for a few days; later, unfortunately a locust attack destroyed the experiment just before this could be done.

soil of Bishop Mahon, this initial watering might have led to progressive leaching down of some of the salt in the soil, with evaporation not contributing enough additional salinity to compensate for this loss. However, in the relatively non-saline soil of St Teresa, the rate of dissolution was not as pronounced and hence could not compensate for the accumulated salt from evaporation or evapotranspiration.

Plant growth and humidity

Of the different techniques that were tried using different moisture-retaining materials in the soil to capture the evaporated water, vapour-fed SAP irrigation produced the tallest growth at the St Teresa site, 36% better than the control (vapour-fed without moisture retaining material) at $p < 0.05$. The organic mulch came second, 18% better than control. However, on the Bishop Mahon site, there was no significant difference in growth when comparing treatments.

On the St Theresa site, the respective performance of the five treatments for mean heights reflected that of their performance for moisture, as can be seen when comparing Tables 2 and 3: The higher the ability of the treatment to retain moisture, the higher the average height of the plants. In particular, the SAP treatment which gave the most growth also retained the most moisture (37% more moisture than the Control, $p = 0.05$), followed by the Organic Mulch (at 32% better than the Control, $p=0.05$) which also was the second best performed for height. The Biochar and the Plastic Sheeting treatment did not show significant differences in performance from both the point of view of plant height and soil moisture, ranking between the organic mulch and the control. The control was the worst performing for plant height and moisture retention.

Therefore, from these preliminary results, it would seem that materials that are able to retain the most moisture also would allow for the largest growth.

However, it also was noted that on both sites there was a steady decline of moisture content in the soil over the duration of the experiment, as apparent in Figures 6 and 7, and the accompanying ANOVA test. The rate of decline was comparable for both sites at around 6% point for both sites after 30 days, suggesting that in both cases the evaporation from the bottle was not compensating for the lack of rain and for the evaporative losses from the soil over the 30 days that the experiment lasted.

It is interesting to note that the plastic sheeting practically prevents evaporation from the soil into the atmosphere by obstruction, which is a different mechanism from that through which materials that absorbs moisture operates (Organic Mulch, SAP and Biochar). This would suggest that evaporative losses when using plastic sheeting might be attributed to evapotranspiration alone, an attribute that perhaps could be used to estimate that parameter in future modelling studies. Also, an improved performance of the vapour-fed irrigation pitchers might be achieved by combining plastic sheeting with one of the materials that absorb moisture (Wang et al., 2010).

Further work

It is suggested that the experiment be repeated, including with the combination of e.g. SAP and mulch, and to full maturation of the crop, which unfortunately was interrupted by a locust attack on this occasion. In addition, water consumption in the bottles should be recorded daily to gain insight into the amount of moisture made available to the plants through this technique and determine the yield for efficiency of water use by the plants.

At Bishop Mahon where both water and soil were excessively saline and sodic, germination and initial establishment of seedlings could be carried out with low salinity water to distinguish the effect of the soil from that of the water, since the initial germination stage was directly using saline water. If this new experiment indicated much better growth of the sorghum, then it would become possible to use the technique even on sites where the soil is very degraded.

Finally, the crude design of the bottle and the arrangement of plants could be improved, for example:-

i) Holes could be placed at different depths, and adjusted as a function of crop or even crop age if it was possible to remove and replace bottles (though this may challenging in sandy soil, unless perhaps roots prevent the flow of sand);
ii) Internal components e.g. wicking materials could improve evaporation rates; an inverted funnel could be added to the bottle to prevent condensate falling back into the pool of saline water;
iii) The top of the holes could be deformed to present a lip that would guide the trickling condensate inside the bottle to the fabric and into the soil;
iv) Crops and holes could be arranged North and South of the bottle while the sun travels from East to West and overhead during the day (Turkana is on the Equator), thus allowing direct sunshine to impinge on the bottle throughout the day and maximise water evaporation. This would help at least in part to mitigate any drop in level of moisture in the soil, as observed during this experiment. Observations of the evolution of moisture content over the full length of the dry season (ca. half a year) would be useful in this respect. Occasional direct watering and the frequency at which it should be conducted might be recommended on the basis of these observations.
v) Combination of treatments may also be helpful, e.g. Plastic Sheeting combined with Organic Mulch as suggested earlier, or Plastic Sheeting or Organic Mulch near the surface together with SAP at depth.
vi) In the future, fully biodegradable SAPs may be desirable (Nnadi and Brave, 2001), which may be better ensured if they could be made from natural products e.g. agricultural waste rather than petrochemicals, in order to avoid potential degradation of the environment by microplastics. The production of a biodegradable SAP produced from orange and avocado peels has been demonstrated by Kiara Nirghin [1] in 2016 (Caruso, 2016).

Conclusions

Ability of the vapour-fed pitcher irrigation method to sustain the growth of sorghum

The experiment fulfilled its first aim by demonstrating that the vapour-fed pitcher irrigation method was able to sustain the growth of dual-purpose sorghum over 30 days on the St Theresa site where the soil was not saline. The only water supplied to the sorghum between day 10 and day 30 came from the remaining water left in the soil from the establishment period of the plant, plus any water that evaporated from the pitcher between day 10 and day 30.

On the Bishop Mahon site where the water and the soil were both more saline than on the St Theresa site, growth was stunted, with the plants barely growing between the 17th day and the 23rd day after planting. It would seem that germination itself may have been stunted by the initial direct application of the saline water during the initial phase of the experiment when establishing the crops. The experiment was also interrupted by an attack of locusts before the data could be obtained for the 30th day after planting.

Comparative effectiveness of moisture retaining materials

The second aim of the experiment was to compare the respective performance of vapour-fed pitcher irrigation

[1] An achievement all the more remarkable given that at the time Ms Nirghin was still a 16 year old.

supplemented with different moisture-retaining materials added to the soil.

On the St Theresa site (where data could be obtained until the 30th day after planting, unlike for the Bishop Mahon site), the respective performance of treatments with respect to mean height reached by plants followed the same order as the amount of moisture that was retained in the soil, that is, the moister the soil, the greater the height.

The best performing treatment was SAP (height 36.6 cm and moisture 22.2 vol.% over 30 days), followed by Organic Mulch (31.8 cm and 21.2 vol.%), then Biochar and Plastic Sheeting (28.9 - 29.8 cm, 19 - 19.2 vol.%, no significant difference), and finally the Control where no moisture retaining material was applied (27.0 cm, 16.1 vol.%) ($p = 0.05$).

Other conclusions

During the experiment, soil salinity increased on one site and decreased on the other site, possibly due to the effect of the direct watering applied to the soil during the initial 10 days of the experiment and the marked differences in salinity between the two soils. Further investigation would be required to investigate this parameter over a much longer period of time.

A steady decrease of the soil moisture level was observed over the course of the experiment, which was similar for both sites. Improved design of the pitchers for greater efficiency of vapour and condensate transmission to soil and roots, and more efficient positioning of plants around the bottles that allow better illumination of the bottle, would help bring more moisture to the plant, as well as a combination of techniques for better conservation of soil moisture such as the combined use of plastic sheeting and moisture-absorbing materials.

Water use efficiency was not determined; hence the authors will repeat the study including this parameter, and will also compare the consistency of new results to this current one. The experiment was also interrupted by locust attacks; hence the weight of grain produced could not be determined. Future experiments will protect the field from locusts and record this data as well as measure water use efficiently, which will enable further development of vapour-fed pitcher irrigation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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