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Development of a Low-Cost Solar-Powered Water Supply System for Small-Scale Drip Irrigation Farms in Sub-Saharan Africa: Dosing Tank and Bell Siphon Perspective

Eric Oppong Danso[1]; Thomas Atta-Darkwa[2]; Finn Plauborg[3]; Edward Benjamin Sabi[4];
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Abstract: A substantial amount of work has been done concerning the use of siphons to automatically start and stop the discharge of fluid in many applications, except for application as a water supply system for smallholder drip irrigation systems. Thus, the main aim of this study was to develop a siphon apparatus and apply it to regulate the low-flow-rate water supply from a solar-powered pump as intermittent doses to pressurize small-scale drip irrigation farms in Sub-Saharan Africa (SSA). A siphon apparatus was assembled from polyvinyl chloride (PVC) pipes and installed in a 210-L tank. A drip irrigation system covering an area of 500 m^2 was connected to the tank containing the siphon, and water was lifted into the tank by a low-capacity 12-V pump that was powered by a 50-W solar panel. The siphon apparatus in the tank was tested over extended periods of time and was shown to work reliably and consistently by automatically and intermittently discharging water to pressurize the drip irrigation laterals, thus being able to irrigate while largely unattended. Test results showed that the inflow rate of 4.75 $L\,min^{-1}$ successfully caused the siphon to start, and the average coefficient of discharge for the siphon was found to be 0.35. Results from water application uniformity tests calculated using the method established by the American Society of Agricultural and Biological Engineers (ASABE) showed average to good discharge uniformity from emitters. The setup cost of the system was USD 415, whereas the net farm income obtained by accounting for all variable costs and annualized capital cost of the irrigation setup was USD 69. We conclude that it should be fairly easy and economically feasible to adapt the dosing siphon, low-flow-rate pump, and solar panel to other small-scale drip irrigation systems that are currently being promoted in SSA. **DOI:** 10.1061/(ASCE)IR.1943-4774.0001315.

Author keywords: Automated irrigation; Poverty alleviation; Low-capacity pump; Water application uniformity; Smallholder farmers.

Introduction

Thirty three of the 54 countries in Sub-Saharan Africa (SSA) are counted among the poorest countries globally and as having the highest poverty rates in the world (Chen and Ravallion 2010; UN-OHRLLS 2003; von Grebmer et al. 2011). Food production in SSA has decreased during the past 50 years with the result being persistent and widespread famine (Baro and Deubel 2006; Devereux 2009). Close to 70% of SSA's ultrapoor people live in rural areas and mostly depend on rainfall in their subsistence farming (Ravallion et al. 2008). However, the rainfall pattern in SSA is characterized by significant variability, with recurrent extreme droughts and severe floods that ultimately reduce food production (Hoscilo et al. 2015).

In the face of unreliable rainfall patterns, irrigated horticultural production has been cited as a potential poverty alleviation tool in SSA. This is because irrigation has the potential to mitigate the negative impact of drought on crop production that threatens the livelihood of many SSA smallholder farmers (Weinberger and Lumpkin 2005). Thus, irrigation is often pointed out as a key component of so-called climate-smart agriculture and sustainable intensification (e.g., Campbell et al. 2014; Pretty and Bharucha 2014; Rockström et al. 2017) that allows insurance against drought, produces higher yields, and creates more seasons per year. However, widespread action to allow smallholders access to water and irrigation has not yet materialized (Burney et al. 2013). SSA generally, with 4% of agricultural land under irrigation, and Ghana in particular, with only 0.5%, lag far behind Asia (37%), where irrigation has catalyzed a major leap in productivity known as the Green Revolution (Burney et al. 2013). Accordingly, a huge yield gap persists in agriculture in SSA due to the lack of irrigation development (Mueller et al. 2012).

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Smallholder farmers in SSA currently grow vegetables by manually fetching water from nearby streams or dug-outs for irrigation. Research carried out in West Africa found manual irrigation to be the most prevalent method for small farms and gardens (Dittoh et al. 2010; Drechsel et al. 2006). However, fetching water with a bucket is tedious and strenuous, requiring roughly 9 h of labor per day to irrigate a plot size of only 1,000 m^2 (Woltering et al. 2011). It is not only laborious but also inefficient because of low water application uniformity and excessive drainage (Batchelor et al. 1996). A suitable alternative to manual irrigation for the smallholder farmer is drip irrigation, which has several benefits compared with manual irrigation. First, drip irrigation wets a small fraction of the soil surface, thereby saving water through a reduction in soil evaporation (Martínez and Reca 2014; Mmolawa and Or 2000; Oppong Danso et al. 2015; Patel and Rajput 2004). Second, fertilizer can be applied efficiently through fertigation, whereby the fertilizer is mixed into the irrigation water to trickle down to the roots (Or and Coelho 1996). Other benefits of drip irrigation include labor saving; minimal leaching of nitrates and other pollutants; reduced pumping costs and energy savings; and potential diversification into higher-value crops (Perry and Steduto 2017).

The normal operation pressure for most conventional drip irrigation systems ranges from 200 to 400 kPa (20 to 40 m water head). However, a pressure head of even 100 kPa (10 m water head) is unaffordable for many smallholder farmers in SSA (Fandika et al. 2011). There are drip irrigation alternatives (e.g., bucket drip) that operate at a low water head (approximately 1–2 m), making them suitable for smallholder farming conditions (Fandika et al. 2011). In the bucket drip system, water is lifted into a slightly raised bucket reservoir to provide pressure to irrigate small pieces of land. Small bucket drip systems serving 10–120 m^2 have received extensive promotion in the developing world, but, as Woltering et al. (2011) pointed out, the adoption of small bucket drip kits in Africa has for various reasons been abysmal. Various studies have found many cases of abandoned bucket drip kits, as reported in Kenya (Kulecho and Weatherhead 2006), Niger (Woltering et al. 2011), South Africa (Sturdy et al. 2008), and Zimbabwe (Belder et al. 2007; Maisiri et al. 2005; Moyo et al. 2006). These studies have shown the high rate of abandonment to be dependent mainly on little or no labor savings, low or no economic advantage, and lack of knowledge and skills. For example, Maisiri et al. (2005) reported from Zimbabwe that the lack of better yield or appreciable economic benefit of a 100-m^2 drip kit over manual bucket irrigation led to large-scale abandonment of kits. Moyo et al. (2006) reported that bucket drip systems covering an area of up to 120 m^2 did not show any significant labor savings when water had to be manually lifted into the bucket reservoir, leading to their mass abandonment. Another reason for low adoption of bucket drip kits is farmers' perception that the risk in adoption is relatively high (Namara et al. 2014). Education, training, and initial trials in farmers' fields is therefore necessary to build the confidence of farmers in any new technology, including the bucket drip, as pointed out by Namara et al. (2014), who found an increase in adoption when comprehensive training was provided together with informational brochures in local languages.

More often, bucket drip kits are promoted as standalone systems without the means of getting water into the bucket reservoir. Merrey and Langan (2014) pointed out that, when considering the promotion of small-scale drip irrigation kits for home gardens and small commercial farms, it is critical to pay attention to the means of filling the bucket reservoir. Consequently, various water-lifting technologies are currently being promoted to accompany the drip kits: manual water fetching, treadle pumps, and motorized pumps (Merrey and Langan 2014). As stated earlier, manual irrigation is laborious and inefficient. Mangisoni (2006) concluded that the treadle pump's capacity to save labor is limited because it is as arduous as a drip kit to operate and needs three people to draw water from a shallow well. Namara et al. (2014) studied farmer assessment of the efficiencies of manual water fetching and the treadle pump in Ghana. The farmers scored the efficiency of the treadle pump secondary to that of manual water fetching, with the result, again, large-scale abandonment. Motorized pumps might seem to be the most suitable alternative in such a situation; however, cost keeps them beyond the reach of many smallholder producers in SSA, where poverty is widespread. A study conducted in SSA by Giordano and de Fraiture (2014) established that the cheapest motorized pump, costing USD 250, is very expensive for many poor farmers. As an alternative, there are relatively cheap and reliable low-capacity pumps that are mostly used in low-volume pumping systems such as minifountains, hydroponic systems, and beverage machines. The problem with such systems is that they are designed for a very low water head and flow rate, making them unsuitable for direct coupling to small-scale drip kits because of poor uniformity. However, for a suction lift of not more than 8 m, a low-capacity pump could be used with a dosing tank and siphon to supply a high flow rate in doses to match the pump's steady, low flow rate. In this way, the siphon regulates the low flow rate from the pump as intermittent doses and potentially improves uniformity of water application compared with direct pumping into drip lines.

The automatic dosing siphon represents a simple and low-cost water supply system to pressurize the bucket drip system. Automatic dosing siphons have been in use for a little over a century (Ball 1996) and are mostly applied whenever automatic starting and stopping of the discharge of fluid is required (Garrett 1991). A siphon apparatus is designed to initiate fluid discharge when the inflow rises to a preset level and to stop it when the fluid discharged drops to a preset level. Thus, the system starts and stops largely unattended. Dosing siphons are frequently applied in aquaculture, where they supply effluent flow as pressurized intermittent doses to remove sediment from reservoir containers (Ebert and Houk 1989). Siphons have also been used for toilet flushing, cleaning stockyards, flushing urinals, draining hydroponic grow beds, and dosing gravity-drain fields, among other purposes. Notwithstanding their widespread appeal, the usefulness of siphons has yet to be extended to pressurizing drip irrigation systems.

The combination of dosing siphons, bucket drip irrigation kits, photovoltaic panels, and low-capacity 12-V pumps can result in a simple, low-cost water supply system for the smallholder farmer in SSA. A photovoltaic bucket drip system relies on the stability of solar energy and its own low energy requirements to irrigate small farms and gardens. These systems have special appeal in off-grid rural communities in SSA, where water fetching for irrigation and domestic use is the job of women and young girls (Blagbrough 2001). Photovoltaic pumping used for small-scale drip irrigation may require no batteries because energy storage can be diverted into the height of the water column in a slightly raised tank, which subsequently distributes the water by gravity. Directly coupling a low-capacity photovoltaic pumping system to a drip irrigation setup without a reservoir tank may result in emitter discharge uniformity problems. The automatic dosing siphon can potentially regulate the flow from the solar pump by automatically breaking it into intermittent, pressurized doses. In this way, two problems are solved at the same time: first, the labor and time required to fill the reservoir and repetitively open a valve in conventional bucket drip systems is eliminated and the new system needs little supervision. Second, the uniformity of the applied water is improved by the regulation of the low flow rate from the solar pump as automatic and intermittent doses.

Table 1. Monthly climate data during the 2015–2016 evaluation of the automated drip system

Parameter	November	December	January	February	March	April
Solar radiation (MJ m^{-2} day^{-1})	14.1	13.9	12.7	14.8	15.7	17.1
Maximum air temperature (°C)	32.9	33.0	33.9	35.9	35.5	35.1
Minimum air temperature (°C)	22.1	20.0	20.6	21.7	22.9	23.3
Wind speed (m s^{-1})	4.0	3.3	4.3	4.4	4.8	5.1
Precipitation (mm)	126.5	27.2	36.8	15.2	228.3	90.4
Reference evapotranspiration (mm/day)[a]	6.9	6.4	7.1	6.9	5.9	5.8

[a] Computed using FAO Penman–Monteith method (Allen et al. 1998).

The use of photovoltaic pumping is expanding globally because it is seen as economical and as promoting a renewable source of energy, especially in off-grid rural communities (Foster and Cota 2014). Additionally, photovoltaic systems are long-lasting, they are unaffected by lack of fuel, have low operating cost, and require low maintenance (Hossain et al. 2015). There has been a steady fall in the price of photovoltaic panels in the last 10 years (Foster and Cota 2014). Indeed, it has decreased by roughly 80% whereas fuel prices have increased by more than 250% (Foster and Cota 2014). Again, photovoltaic pumping systems are rated to last for 25 years with a payback duration of just 2–3 years (Foster and Cota 2014). Several studies have found photovoltaic water pumping to be economically viable compared with fuel-driven pumping. For example, Zieroth (2005), in his Mauke, Cook Island study, concluded that solar pumping is economically superior to diesel pumping. The price for solar water pumping in Mauke was USD 0.16/m^3, whereas the price for diesel pumping was USD 0.22/m^3. Curtis (2010) concluded that solar-powered irrigation in western Utah is a profitable substitute for the diesel pumping currently used for fodder cultivation. He reported that the yearly net farm return per hectare increased from USD 1,395.17 to USD 5,449.10.

Our literature search showed that the use of a dosing siphon to automatically break up high irrigation system flow rates into intermittent doses to achieve the steady, low flow rate required by a solar pump has yet to be tested. It also revealed that there has as yet been no attempt to integrate dosing siphons, photovoltaic panels, low-capacity pumps, and bucket drip kits to serve the smallholder farmer in SSA. The aim of the present study was therefore to build a simple and low-cost solar-powered water supply system and integrate it with a bucket drip system using the principle behind the dosing siphon. The specific objectives of the study were (1) to determine the uniformity of water application by the system and (2) to carry out an economic analysis of the system.

Materials and Methods

Site Description

A siphon apparatus was developed and installed in a 210-L tank. Its purpose was to break up a low-flow-rate water supply from a solar pump into intermittent doses to pressurize a drip irrigation setup covering an area of 500 m^2. The study was performed at the University of Ghana's Forest and Horticultural Crops Research Centre (FOHCREC) in Kade, Ghana (N060° 08′ 37″N, 000° 54″ 10″W; 180 m above sea level). FOHCREC lies in the forest zone with an annual rainfall ranging 1,300–1,800 mm (Nkansah et al. 2007; Ofosu-Budu 2003) and characterized by an April–July main rainy season and a September–October minor rainy season. The dry season starts in November and ends in March. Climate data during the evaluation period in 2015–2016 are provided in Table 1.

Mode of Operation of an Automated Siphon

The various parts of a typical automatic dosing siphon are shown in Fig. 1. The principles behind the operation of the siphon are shown in Fig. 2. The siphon assembly is principally composed of a bell and a trap. The nominal diameter of the bell pipe is approximately thrice that of the trap. The trap portion of the siphon is further divided into a short leg, a long leg, and a trap depth (Fig. 1). Before operation, the trap depth is filled with water [Fig. 2(a)]. This is done

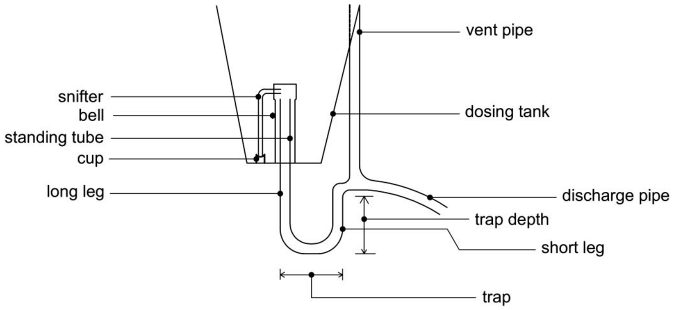

Fig. 1. Various parts of a typical bell siphon.

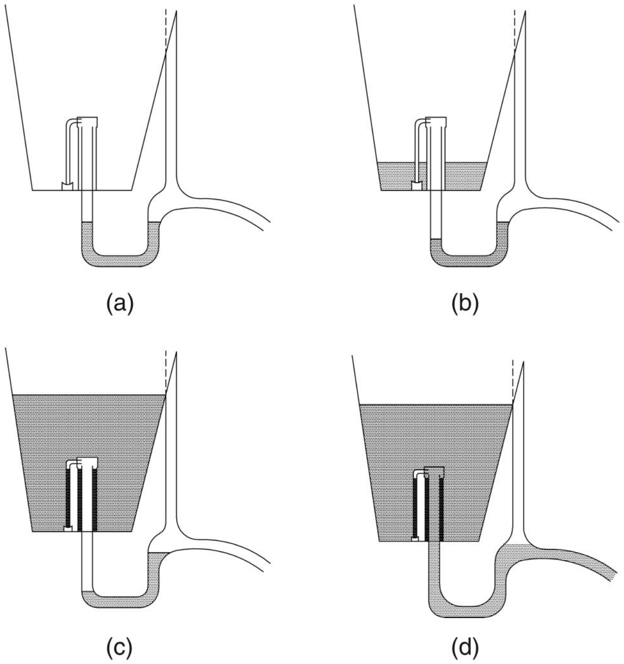

Fig. 2. Variations in siphon processes for (a) primed trap; (b) trapped air in bell; (c) at the point of discharge; and (d) during discharge for a typical bell siphon.

by temporarily sealing the open end of the discharge pipe and pouring water through the vent pipe. When the trap depth is completely filled with water, the seal on the discharge pipe is removed and water is then pumped into the dosing tank (i.e., the tank that houses the bell). As water is pumped into the dosing tank, the water level begins to rise in the dosing tank until it reaches the tip of the snifter, where it locks air inside the bell and blocks it from escaping [Fig. 2(b)]. As the pump continues to fill the dosing tank, the water level rises further until it overflows the base of the snifter and the bell. At this point, air pressure is built up in the bell and the resulting pressure pushes the water in the trap toward the discharge pipe [Fig. 2(c)]. As the volume of water in the dosing tank continues to increase, it equally increases in the bell and exerts additional pressure on the locked air. As the pressure on the locked air builds up, the air pressure in the bell increases, thereby pushing the water in the trap until the locked air is forced to leave the trap through the air release vent. Soon after the release of the locked air, the siphon begins to discharge at the moment that the water bursts into the long leg of the trap to follow the released air [Fig. 2(d)]. The discharge continues until the water level in the dosing tank falls beneath the base of the bell, drawing air into the bell to stop the discharge. When the discharge is complete, the inflow from the pump blocks the base of the bell faster than the bell can be completely refilled with air. The snifter pipe, the base of which is approximately 3 cm above the base of the bell and the placement of which is inside a small cup, guarantees a successful refill of the bell with air at the end of each siphon event.

Automatic Dosing Siphon Construction

A bell siphon apparatus was assembled from PVC pipes and fittings. It was set up in a 210-L plastic tank. The bell was fabricated by gluing a pipe cap of 76-mm nominal inside diameter (ID) to a 30-cm length of pipe of 76-mm nominal ID. A hole of 13-mm diameter to hold a nominal 13-mm male adapter was drilled and tapped into the top (capped end) of the bell. The threaded hole was used to attach the snifter pipe to the bell. The snifter pipe was constructed from pipe and elbows of 13-mm nominal ID. A 25-mm-diameter hole was drilled and tapped at the center of the base of the dosing tank to receive the long leg of the trap through a 25-mm nominal male threaded adapter. The long leg of the trap was pushed into the dosing tank until the required length was obtained. Approximately six small notches were cut into the bottom end of the bell, which was then was placed notches down over the long leg of the trap. It was secured to the long leg of the trap by a 4-kg iron rod on its top. Finally, the discharge pipe was extended downward to facilitate connection to the drip system using a 25-mm elbow and one piece of the 25-mm PVC pipe.

Siphon Flow Rate Measurements

The flow rate of a siphon is dependent on the head from the surface of the water in the dosing tank to the end of the standpipe (Garrett 1991). It can be described by a function between the diameter of the trap and the head (Mote et al. 1983). The equation by Bradbury (1910) gives the average flow rate from a siphon as

$$Q = K \times A\sqrt{2 \times g \times h} \tag{1}$$

where Q = flow rate ($\mathrm{L\,min^{-1}}$); K = discharge coefficient; A = inner area of the discharge pipe ($\mathrm{m^2}$); h = average head [= average of maximum and minimum head (mm)]; and g = acceleration due to gravity ($\mathrm{mm\,min^{-2}}$).

In our case the head was taken as the distance from the water level in the dosing tank to the final part of the discharge pipe. For the siphon flow rate measurement, this distance was varied several times by marking the inside of the dosing tank at four heights with a carpenter's tape and a permanent marker (starting at 80 cm with 20-cm increments except for the last one, which was marked only when the siphon sniffed air through the snifter pipe). Water was then pumped into the dosing tank using a 12-V pump and a 50-W solar panel. At the point of siphon discharge, the pump was turned off to stop the water flow into the dosing tank. A container to receive the discharging water was then placed under the discharge pipe and a stopwatch was started. As the water discharged and reached the next marked level, a valve on the discharging pipe was closed and the filled container under the discharge pipe was emptied into a graduated cylinder so that the volume of water could be read. At the end of each interval of the marked heights, the emptied container was again placed under the discharge pipe, and the procedure continued until all the marked heights were covered. During each discharge interval, the starting and ending marked heights were taken as maximum and minimum heads, respectively. The measurements were repeated three times, and the mean was used to calculate the discharge coefficient using Eq. (1).

Pump Performance and Minimum Inflow Rate Determination

Reliable siphon cyclic action is largely dependent on the inflow rate. If the siphon is unable to start, the inflow is too slow and the rate should be increased (Garrett 1991). On the other hand, if the siphon does not stop, the inflow is too fast and the rate must be decreased (Garrett 1991). For reliable siphon operation, then, the minimum and maximum inflow rates into the dosing tank should be investigated. Because the inflow into the dosing tank depends on the capacity of the pump, which is also a function of the pumping height, a test was carried out to determine the pump's flow rate against various pumping lifts. The pump for the system was a 12-V direct current (DC) 24-W centrifugal pump. It had a shutoff head of 6 m and a flow rate of 800 $\mathrm{L\,h^{-1}}$ at zero total dynamic head (pumping height). In our case, the pumping height was the interval between the water level in a dam to the top of the dosing tank. To develop a pump curve, the pumping height was varied five times starting at 210 cm to a maximum of 520 cm. In each case, as the pump was turned on, a stopwatch was started and the outlet hose was directed to a bucket for 10 min. At the end of the 10-min interval, for a particular pumping height, the filled bucket was poured into a graduated cylinder to measure the volume of water pumped and subsequently the pumping rate ($\mathrm{L\,min^{-1}}$). The measurements continued until we reached a height where the pump could not lift water. Finally, a second-degree polynomial was fitted between height and pumping rate.

After determining the inflow rate from the water level in the dam to the top of the dosing tank, the minimum inflow rate into the dosing tank for a successful siphon cyclic action was investigated. This test was conducted using the 12-V DC pump and the 50-W solar panel. A valve was connected to the inlet pipe such that the inflow into the dosing tank could be regulated. The flow rate from the inlet pipe into the dosing tank was determined several times by adjusting the valve. First, the valve was fully opened and water flow from the pipe into the dosing tank was collected over a period of time and subsequently poured into a graduated cylinder to determine the flow rate. If siphoning initiated properly when filled up by the pump at the determined flow rate, but could not break successfully, the flow rate from the inlet pipe into the dosing tank was reduced by partially closing the valve. The dosing tank was then filled using the new lowered flow rate. This exercise was repeated until an optimum pumping rate that successfully caused the siphon to start and stop repeatedly was obtained. This flow rate was noted as the optimum design flow rate for the setup.

Connection of Siphon Assembly to Drip Irrigation System

A 50-W photovoltaic solar panel (Yingli, Sydney, Australia) was coupled to a 12-V DC pump (Qingdao Ahead Electric, Quindao, China) to pump water into the 210-L tank that housed the bell. Water was pumped from a nearby dam into the dosing tank. To give the pump some protection, a filter was placed in front of it to reduce the amount of trash and debris entering it. To ensure long-term functioning of the siphon before connecting the drip laterals, the setup was operated daily from November 1, 2015, to January 31, 2016, in order to detect any failure in either siphon discharge or siphon break action.

Water discharged by the siphon was filtered using a 125-μ-diameter (120-mesh) screen filter (Naandanjain, Jalgaon, India) before connecting to a 25-mm polyethylene mainline. Standard 12-mm drip laterals (Naandanjain) with emitters (pressure-compensated) spaced at 30 cm were cut into 20-m lengths and connected to the 25-mm mainline at a row spacing of 50 cm. The plot was 20 m long and 25 m wide and had 48 drip laterals laid out alongside each crop row with an emitter discharge rate of 1.7 $\mathrm{L\,h^{-1}}$ at 100-kPa pressure. After connecting the drip irrigation system to the siphon assembly, the entire setup was again run daily from February 1, 2016, to April 30, 2016, to ensure operational reliability of the system.

Evaluation of Water Application Uniformity

Water application uniformity was evaluated for two water supply systems: (1) the dosing siphon–based system (SWS) and (2) the pump-drip–coupled system (PWS). The most widely accepted parameters to evaluate drip emitter discharge uniformity as outlined by ASABE (2008, 1999) are emitter flow rate variation (q_{var}), emitter discharge coefficient of variation (C_v), and emission uniformity (E_u). The emitter flow rate variation was calculated as follows:

$$q_{\mathrm{var}} = \frac{q_{\max} - q_{\min}}{q_{\max}} \qquad (2)$$

where $q_{\max}$ = maximum emitter flow rate ($\mathrm{L\,h^{-1}}$); and $q_{\min}$ = minimum emitter flow rate ($\mathrm{L\,h^{-1}}$).

The emitter discharge coefficient of variation was calculated as

$$C_v = \frac{s_q}{\bar{q}} \qquad (3)$$

where s_q = standard deviation of emitter flow rate ($\mathrm{L\,h^{-1}}$); and $\bar{q}$ = average emitter flow rate ($\mathrm{L\,h^{-1}}$).

The standard deviation of emitter flow rate was calculated as

$$S_q = \sqrt{\frac{\sum_{i=1}^{n}(q - \bar{q})^2}{n-1}} \qquad (4)$$

where n = number of emitters evaluated; and q_i = individual emitter flow rate ($\mathrm{L\,h^{-1}}$).

The average emitter flow rate was computed using the equation

$$\bar{q} = \frac{1}{n}\sum_{i=1}^{n} q_i \qquad (5)$$

Table 2. Criteria for acceptable drip uniformity parameters

Classification	Parameter q_{var} (%)	 C_v (%)	 E_u (%)
Excellent	—	<5	>90
Good	—	—	90–80
Fair	—	—	80–70
Desirable	<10	—	—
Average	—	5–7	—
Marginal	—	7–11	—
Acceptable	10–20	—	—
Poor	—	11–15	70–60
Unacceptable	>20	>15	<60

Source: Data from ASABE (2008, 1999).

The emission uniformity (E_u) was calculated using the equation

$$E_u = 100\left[1 - 1.27\frac{C_V}{\sqrt{\grave{n}}}\right]\left(\frac{q_{\min}}{\bar{q}}\right) \qquad (6)$$

where $\grave{n}$ = number of emitters per plant.

The acceptability criteria for the uniformity parameters using the ASABE standards (2008, 1999) are given in Table 2.

Emitter Flow Rate Measurement

The uniformity parameters required measurement of the emitter flow rate. The first measurement was for the SWS. For the emitter flow rate measurements, the field was divided into three equal segments in order to distribute the measurement points evenly throughout the field. A total of 100 emitters were randomly selected to correspond approximately to near the main line, midway from the main line, and at the distant end from the main line. For each measurement, 0.5-L catch cans were placed under the emitters and water was collected after two discharges by the siphon over 16 min. The measurements were done on a clear day at solar noon and repeated four times. Water collected in the catch cans was weighed using an electronic balance. The weight of the water in the catch cans, together with the density of water (1 $\mathrm{g\,cm^{-3}}$), was used to calculate the volume captured by the catch cans. Thereafter, the pump was directly connected to the 25-mm main line and the procedure was repeated to determine the emitter flow rate for the PWS.

Economics

Economic analysis of the SWS was done by considering the cost of the irrigation system and the variable cost associated with using the system to grow okra for one season. The variable cost considered included labor (field preparation, sowing, weeding, insecticide and fungicide application, and harvesting), farm inputs (insecticide, fungicide, hoe, and fertilizer), and irrigation water. Setup cost was calculated by annualizing the capital cost of the irrigation setup for a period of five years at a discount rate of 5%. The annualized cost was calculated as

$$AC = \frac{Cs \times r}{1 - (1 + r)^{-n}} \qquad (7)$$

where AC = annualized cost of the irrigation setup (USD); Cs = initial cost of irrigation setup (USD); r = discount rate (%); and n = expected lifespan of the irrigation setup (years).

The price of water was obtained from Ghana Water Company charges. Gross income was estimated based on a projected yield of approximately 1,000 kg of okra/500 m^2 (Oppong Danso et al. 2015). Net income was computed by subtracting cost of production from gross income. Gross margin and net income were used to access the economic feasibility of the system. Gross margin was computed as gross income minus total variable costs; net farm income was calculated as gross margin minus annualized capital cost of the irrigation setup.

Results and Discussion

Pump Performance and Siphon Evaluation

The relationship between the pump's flow rate and the pumping height is shown in Fig. 3. Examining the data from pump tests shows that the pump's flow rate was closely related to the pumping height and that the relation was a second-degree polynomial (Fig. 3). It can be inferred from Fig. 3. that the rate of flow into the dosing tank at 240 cm (height from the surface of dam to the top of the dosing tank) was 7.5 L min^{-1}. At an inflow rate of 7.5 L min^{-1} the siphon was able to start successfully but could not stop at the end of the discharge. This could be attributed to the inflow being high enough to equal or surpass the minimal speed with which air could enter the bell to break the siphon. When this occurred, there was equilibrium between inflow and outflow and the siphon did not stop. As reported by Mote et al. (1983), flow rate into a dosing tank for successful siphon operation is not precisely stated in the literature; rather, it depends mainly on the volume of the dosing tank and the trap depth. In our case, the optimum rate of flow into the dosing tank that was successfully able to trigger and break the siphon was 4.75 L min^{-1}.

There was a strong linear relationship between the head and the siphon flow rate for the tested siphon, with a coefficient of determination of 0.99 (Fig. 4). Thus, the equation shown in Fig. 4 was the design equation for the evaluated siphon. The plotted points in Fig. 4. are average values from three repetitions. The mean head and flow rate data from the water level in the dosing tank to the outlet of the discharge pipe for the tested siphon was used in the computation of K values in Eq. (1); the results are provided in Table 3. Bradbury (1910) Gavett (1920), and Mote et al. (1983) reported similar K values for siphons with a 25-mm-diameter discharge pipe.

Fig. 5 shows the constructed siphon together with the dosing tank. It took approximately 40 min to fill the dosing tank at the regulated flow rate of 4.75 L min^{-1}. Siphoning was triggered when the dosing tank was filled to the 200-L mark, and the siphon successfully sniffed air to break the siphoning when the discharging water reached the 10-L mark. The drip irrigation laterals were then connected to the siphon assembly and the setup put in operation again for 90 days. During this period, the system automatically and intermittently produced 842 doses without any failures.

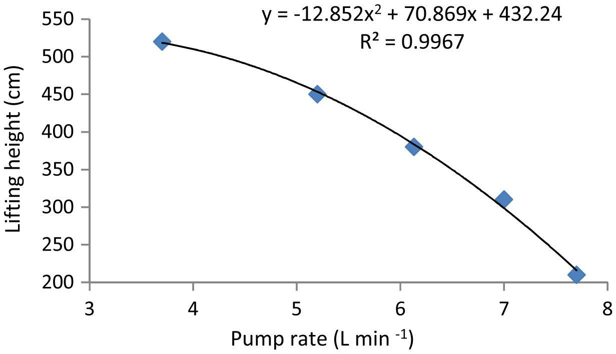

Fig. 3. Head (lifting height) versus flow rate for pump fit to quadratic equation.

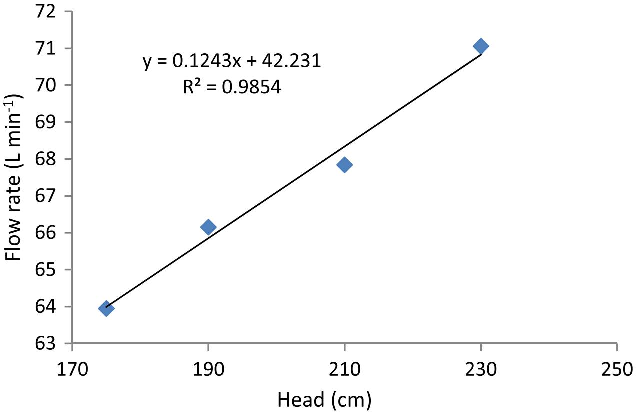

Fig. 4. Siphon flow rate versus head.

Table 3. Flow rate and calculated discharge coefficient for the constructed PVC siphon

Average head (cm)	Average discharge (L min^{-1})	Discharge coefficient, K
230	71.06	0.34
210	67.84	0.34
190	66.15	0.35
175	63.95	0.35

Water Application Uniformity

The uniformity parameters evaluated for the two water supply systems are given in Table 4. The two systems varied considerably when their uniformity parameters were compared. For the SWS, mean C_v was 5.8, with values ranging from 5.7 to 5.9; E_u ranged from 88.4 to 88.6, with a mean value of 88.5; and q_{var} values were low, ranging from 19.8 to 20.2, with a mean value of 20.0. The average emitter discharge was low, ranging from 0.361 to 0.364 L h^{-1}, with a mean value of 0.362 L h^{-1}. Compared with the SWS, all uniformity parameters calculated for the PWS, with the pump directly connected to the drip system, reflected abysmally lower system uniformity. The C_v values of the PWS compared with the SWS were very high ranging, from 64.6 to 65.0, with a mean value of 64.9. When compared with those of the SWS, the E_u values of the PWS were woefully low, with values ranging from 20.9 to 21.2 and a mean value of 21.2. The q_{var} values were also very high compared with the SWS q_{var} values, ranging from 92.8 to 93.4, with a mean value of 93.1. Again, the emitter discharge values of the PSW was comparatively low, ranging from 0.104 to 0.107 L h^{-1}, with a mean value of 0.105 L h^{-1}.

Comparison of the uniformity parameters of the SWS with the ASABE standards showed good to average uniformity (Table 4). All SWS uniformity values were overwhelmingly better than the PSW uniformity values, all of which indicated unacceptably low uniformity. The terribly low uniformity of the PWS compared with the SWS may be attributed to the rather low inlet pressure produced by the low-capacity pump. At zero pumping height, the flow rate from the pump was a paltry 800 L h^{-1} against an average flow from the dosing tank and siphon of 4,035 L h^{-1}—approximately an

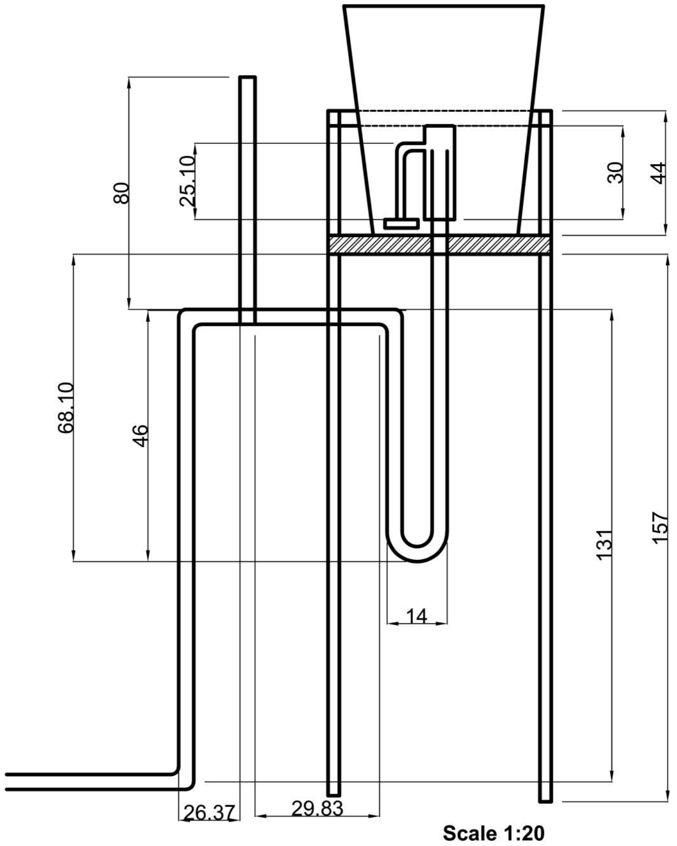

Fig. 5. Bell siphon assembly constructed from PVC pipe and fittings (in centimeters).

80% difference. This means that the SWS is the superior method for pressurizing a small-scale drip system with a relatively cheap but low-capacity pump.

Economic and System Capacity Evaluation

During the dry season in many SSA countries, vegetable production virtually comes to an end due to little or no rainfall, with the result of inflated vegetable market prices. For this reason, the proposed system was used to cultivate okra during the dry season in 2016, and the economics were computed based on the annualized cost of the irrigation setup and the variable costs of one dry season of okra cultivation. For poor smallholder farmers in SSA, irrigated horticultural production is an expensive enterprise. Farmers who wanted the SWS solar drip irrigation system would have to invest in a solar panel and pump, a dosing tank and stand, drip irrigation hardware, and PVC pipes. It can be seen from Table 5 that investing in the SWS system would cost a little over USD 400 whereas the variable cost of using the system for one season to grow okra would be USD 315. Water alone accounted for close to 80% of the total variable cost during the test season of okra cultivation with the system. In situations where access to irrigation water is free, as is the case in many SSA countries, the total variable cost would be only USD 64. With the cost of the SWS annualized, the setup cost for a five-year life period at a discount rate of 5% would be USD 95.76. The gross margin and the net farm income would be USD 164.88 and USD 69.12, respectively (Table 5). Additional revenue might be obtained in places where supplemental irrigation during the major and minor rainy seasons allowed one or two additional growing seasons per year (depending on rainfall and soil type).

Because the gross margin and the net farm income from the analysis yielded positive values, it can be inferred that smallholder vegetable farmers can viably invest in the SWS solar drip irrigation system.

From the climate data provided in Table 1 and the monthly doses in Table 6, it can also be inferred that the system would operate a deficit irrigation strategy where the amount of water used was below the potential evapotranspiration. However, the soil plus rainfall might act as a buffer to offset any drought stress that developed, depending on soil type and water-holding capacity. The 842 doses of 190 L in 90 days gave an average gross daily irrigation application of 1,778 $\mathrm{L\,day^{-1}}$, which is equivalent to 3.6 $\mathrm{mm\,day^{-1}}$ on a plot size of 500 $\mathrm{m^2}$ area. The average climate data from Table 1 give a mean daily evapotranspiration of 6.5 mm, resulting in a daily deficit of 2.9 mm. This means that, in a location where the climate had potential evapotranspiration of more than 3.6 mm, the system would not meet peak water demand; in the current situation, the expected daily deficit was calculated as 45% less than peak water demand. On the other hand, and as seen from Table 1, there was a total of 524.4 mm of rainfall during the November–April evaluation period. It may therefore be argued that rainfall in combination with soil water holding capacity would act as a buffer to forestall drought stress from the deficit in irrigation water supply.

Conclusions

A siphon apparatus was assembled, evaluated, and used as a simple and low-cost way to break up high irrigation system flow rate in doses to match the steady, low-flow rate of a solar-powered supply

Table 4. Emitter discharge uniformity parameters for siphon-powered and pump-powered drip irrigation systems

Number of tests	Number of emitters	$\bar{q}$ ($\mathrm{L\,h^{-1}}$)	q_{var} (%)	C_v (%)	E_u (%)
Siphon-powered system					
1	100	0.361	19.8	5.9	88.4
2	100	0.361	19.9	5.9	88.4
3	100	0.363	20.1	5.7	88.4
4	100	0.364	20.2	5.7	88.6
Mean	—	0.362	20.0	5.8	88.5
Acceptability criteria	—	—	Acceptable	Average	Good
Pump-powered drip system					
1	100	0.104	92.8	64.6	21.3
2	100	0.107	93.4	65.1	21.4
3	100	0.106	93.3	65.0	21.2
4	100	0.105	93.0	64.8	20.9
Mean	—	0.105	93.1	64.9	21.2
Acceptability criteria	—	—	Unacceptable	Unacceptable	Unacceptable

Table 5. Parameters for economic analysis of 500-m^2 dosing siphon solar irrigation system

Parameter	Amount (USD)
Variable cost	
Farm input	16.61
Labor	47.66
Irrigation water	250.3
Total variable cost	314.57
Initial cost of irrigation setup	
Drip hardware and PE pipes	153.49
PVC pipes and fittings	56.55
Dosing tank and stand	113.38
Solar panel, pump, and electrical cables	91.16
Cost of irrigation setup	414.58
Annualized cost of irrigation setup	
Cost of irrigation setup	95.76
Total production cost	410.33
Gross revenue	479.45
Gross margin	164.88
Net farm income	69.12

Table 6. Number of monthly siphon doses during 2015–2016 system evaluation period

Month	Number
February	280
March	281
April	281
Total	842

pump for small-scale drip irrigation systems in SSA. A pumping rate of 4.75 $\mathrm{L\,min^{-1}}$ was enough for proper operation of the siphon. With a discharge coefficient of 0.35, the siphon apparatus was able to pressurize a drip irrigation setup covering an area of 500 m^2 without failure for extended periods. The automated drip irrigation system can be expected to apply water uniformly, as shown by uniformity parameters with good to average values based on ASABE standards. Economic analysis showed the proposed system to be an economically profitable investment for SSA farmers. It should be fairly easy to adapt the dosing siphon, the low-flow-rate pump, and the solar panel to other small-scale drip irrigation systems that are currently been promoted in SSA.

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