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Hydraulics, uniformity, yield and water productivity performance of an innovative bamboo-drip system in rural and peri-urban West-Africa

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Abstract: Despite its broad set of production opportunities in regions subject to scarce water supply, conventional drip irrigation is still expensive and therefore slowly adopted in West-Africa where 80% of vegetable gardens and small farms are still hand-watered. Therefore, we created an affordable bamboo-drip system and assessed its performance with regards to hydraulics and uniformity (in laboratory), and yield and water productivity (in situ). In laboratory, the bamboo system was tested at four pressure heads. For hydraulics performance, coefficients of variation of emitter flow were determined with regards to the bamboo material, emitter precision and emitter plugging, and compared to ASAE EP405.1 standards. Plugging was revealed to be the most important factor causing emitter flow to vary in the bamboo system. For uniformity performance, Christiansen uniformity coefficient was determined and compared to ASABE EP458 standards. The system proved to have good and similar uniformity as conventional drip systems under suitable pressure conditions. In situ, an experiment was conducted in a farmer's field (South-west Benin) in 2015, and repeated in 2016. Tomato was the test crop and the design a three-plot randomized block with three repetitions, each block confronting the bamboo-drip system to plastic-drip and traditional watering can systems. Yield and irrigation water productivity were determined and compared between systems using one-way analysis of variance (ANOVA) under STATA 13.0 program, and at 5% significance level. The bamboo system reached yields in the range of two other systems in both cropping seasons. Its water productivity was similar to that of the plastic-drip system, but 99 and 85% higher than that of the watering can system in 2015 and 2016 respectively. The bamboo system holds promises to enable a more productive use of water at small scale and improve household economy in rural and peri-urban West-Africa.

Key words: Flow, variation, plugging

1. INTRODUCTION

Fresh water resources are limited and expected to become more variable due to climate and land use changes. Demand is forecasted to rise and therefore, gaps between supply and demand might occur (Hall *et al.*, 2008). Irrigated agriculture, by far the biggest water user globally (Rosegrant *et al.*, 2002), has low efficiencies which urgently need to be improved. A promising approach to do so is drip irrigation, precise and frequent application of water as discrete drops, tiny streams or miniature sprays through pressure reducing water paths and emitters (Ngigi *et al.*, 2000). One of its main advantages is the reduction in conveyance loss and water use for growing crops (Ngigi *et al.*, 2001). Indeed, its field application efficiency can be as high as 90% compared to 60-80% for sprinkler and 50-60% for surface irrigation. Apart from improving water distribution uniformity, drip irrigation also increases plant yields, reduces evaporation and deep percolation and decreases risks of soil degradation and salinity (Karlberg and Penning de Vries, 2004). In 1986, Phene *et al.* have demonstrated significant yield increases in tomato production with the use of high frequency Surface Drip Irrigation and precise fertility management. Yield increases were also demonstrated in productions like alfalfa (Hutmacher *et al.*, 1996) and cotton (Ayars *et al.*, 1998) using drip systems. Yet, despite their several advantages and the huge need of irrigation systems for crops such as vegetables, drip systems are adopted by very few producers in developing countries for various reasons among which the main is high equipment cost. Indeed, conventional drip systems have capital costs ranging between US$ 1500 and 2500 per hectare, whereas the vast majority of farmers in developing countries have small landholdings and limited financial resources (Postel *et al.*, 2001). This lack of financial resources for operation, maintenance and management is one of the major reasons for the low application of drip systems in developing countries (Gerards, 1992), as making them economically and technically unavailable to farmers. In this context, developing low-cost drip systems while maintaining advantages of conventional ones in terms of water saving could be of great interest for smallholder farmers in general and vegetable producers in particular.

Low-cost drip systems are commensurate drip technologies for low-income farmers. Such systems would present opportunities that might support a substantial increase of farmers' economic and food security in developing countries. Considerable research was therefore conducted in this domain with much success (Musonda, 2000) and some less costly systems are available nowadays, the most common being drum and bucket kits (Cornish and Brabben, 2001) and Nica Irrigation kit. Recently in Nigeria, a more affordable system incorporating electrical conduit pipes as laterals and medical perfusion sets as emitters was successfully constructed and evaluated (Mofoke *et al.*, 2004). Its hydraulic performance was satisfactory (96.2% application efficiency, 90.8% irrigation efficiency, 92.9 distribution uniformity and 94.3% irrigation adequacy) as the emitters had provisions for flow regulation and were adjusted to deliver the pre-calculated water flow. But still, this system is expensive due to PVC and electrical conduit pipes which remain difficult to afford by smallholder farmers. An alternative to this system is to use bamboo in replacement of PVC pipes, and hand-made pen tube emitters in replacement of perfusion sets. Bamboo (*Bambusa vulgaris* Schrad) is widely distributed in tropical zones (Dierick *et al.*, 2010) and offers stable characteristics, making it suitable for various uses (Lee *et al.*, 2012) among which drip irrigation (Singh, 2010). In West-Africa, the species *Oxytenanthera abyssinica* (A. Rich) Munro is very abundant. It is a lowland, drought-resistant and woody perennial bamboo with hollow internodes and interesting mechanical properties (Lin *et al.*, 2002). Internodes can reach 7-15 cm diameter and 15-30(-40) cm length (Ohrnberger and Goerrings, 1988) and can therefore be used to form water-pipes of different sizes. Ball-pen tubes are cheap and easily accessible to smallholder farmers, who can make their own emitters out of them. Although the bamboo system would have several advantages over other irrigation systems, it would be impossible for it (as for conventional plastic-drip systems) to have hundred percent water application uniformity across fields, due to inherent variabilities in its hydraulics (Zhu *et al.*, 2009) which must then be assessed. As a result of these variabilities, how uniformly the bamboo system can apply water to the plants should also be investigated.

Among other advantages drip irrigation offers over surface and sprinkler systems is the reduction in total plant water requirement, important water savings (by supplying only the water transpired by plants) (Mathieu *et al.*, 2007), reduction of soil water stress and increase of yields (by providing a constant water supply in the root zone) (Liao *et al.*, 2008), increase of irrigation water productivity (Rodriguez-Diaz *et al.*, 2004). Drip irrigation also presents direct advantages to plants' health, since it applies water under the canopy and keeps foliage dry, reducing the incubation and development of many pathogens. By reducing the soil wetted area and creating a drier soil surface, it also reduces the incidence of pest and weed invasion (Simonne *et al.*, 2008). These advantages give drip irrigation a high yield and water productivity potential, and a broader set of production opportunities in regions subject to scarce water supply such as West-Africa. Especially under conditions of small-scale irrigation such as gardens which are still hand-watered at 80% using watering cans, buckets or calabash (Dittoh *et al.*, 2010), drip irrigation and particularly the bamboo-drip system has the potential to boost yield and water productivity. This potential should be investigated in field conditions, in comparison to the reference situation (traditional watering can system) and the ideal one (conventional plastic-drip system).

In the light of the above, this study was initiated and aimed to assess the bamboo system's performance with regards to (i) inherent variabilities in hydraulics and uniformity (in laboratory) and (ii) yield and water productivity (*in situ*).

2. MATERIALS AND METHODS

2.1 Construction of the bamboo system

Bamboo internodes (20 cm long) were used to construct the drip lines. They were first fried into candle wax to get the starch to leach, fasten drying process, reduce water absorption during future use and increase resistance against micro-organisms. Second, their inner parts were very slightly coated with wax again, to protect from rot and reduce friction head losses during irrigation. After these treatments, they were glued to one another with strong and waterproof glue to form irrigation lines. Main and laterals were respectively 16 and 8 mm inner diameter (ID), and 2.4 and 5 m length. Emitters were tortuous-path G type, regulatory, non-pressure compensating and directed upward. They were hand-made from 2 mm ID ball-pen tube pieces. Basal opening was closed and three small V-openings made alongside to regulate flow by up and down movement into bamboo pipes. Figure 1 shows the bamboo system and its main components.

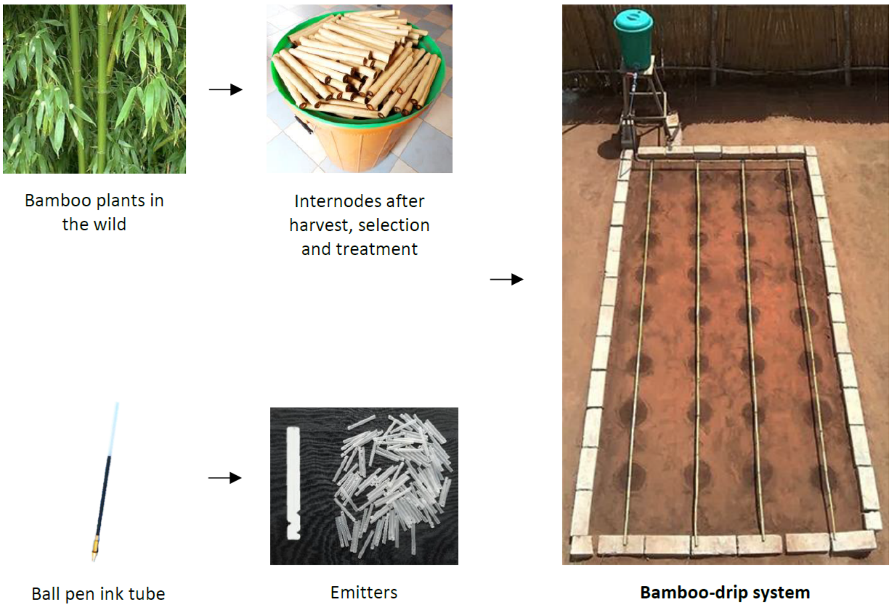

Figure 1. Bamboo system and its main components.

2.2 Assessment of inherent variabilities in hydraulics

Variabilities in a drip system's hydraulics are generally due to pipe material (bamboo material in this case), emitters' precision, temperature effects and potential plugging of emitters. But temperature effects can be neglected as emitters are turbulent flow (Wu and Phene, 1984). Coefficients of variation of emitter flow were then determined for the three remaining factors, i.e. bamboo material, emitters' precision and plugging of emitters, and compared to ASAE EP405.1 standards (ASAE EP405.1, 2000). Tests were conducted at four (04) pressure heads (20, 40, 60 and 80 cm), as emitter flowrates of drip systems have different responses to pressure variations (Badr *et al.*, 2009). Parameters and test methods are:

- **CV (H)**: it expresses how much emitter flow variation is caused by the bamboo material. Three (03) 5 m laterals were tested three (03) times each, and for 30 minutes. Volumetric method was used to determine lateral outlet flow and CV (H) calculated as:

$$\text{CV (H)} = \frac{Sl}{ql} \tag{1}$$

$\overline{ql}$ and *Sl* being respectively average and standard deviation of lateral outlet flow.

- **CV (M)**: it expresses how much emitter flow variation is caused by emitters' precision. Three (03) emitters were tested three (03) times each, and for 30 minutes. Volumetric method was used to determine emitter outlet flow and CV (M) calculated as**:**

$$\text{CV (M)} = \frac{Se}{\overline{qe}} \tag{2}$$

$\overline{qe}$ and *Se* being respectively average and standard deviation of emitter flow.

- **CV (P)**: it expresses how much emitter flow variation is caused by emitter plugging. It was deduced from the coefficient of variation of emitter flow due to the combination of bamboo material, emitter precision and emitter plugging CV (HMP) as follows (Bralts et al., 1981):

$$\text{CV (P)} = \sqrt{\text{CV}^2(\text{HMP}) - \text{CV}^2(\text{HM})} \tag{3}$$

$$\text{with CV (HMP)} = \sqrt{\frac{\text{CV}^2(\text{H})+\text{CV}^2(\text{M})}{1-\text{P}} + \frac{\text{P}}{1-\text{P}}}$$

$$\text{and CV (HM)} = \sqrt{\text{CV}^2(\text{H}) + \text{CV}^2(\text{M})}$$

CV (H) and CV (M) are as previously defined. CV (HM) express how much emitter flow variation is caused by the combination bamboo material and emitter precision. P is the highest value of emitter flow reduction.

2.3 Assessment of emitter flow uniformity

Emitter flow uniformity in the bamboo system shows how much water flow varies from one emitter to the other. At the same pressure heads as previously (i.e. 20, 40, 60 and 80 cm), the bamboo system was tested for 30 minutes. Emitter flows were determined using volumetric method. Uniformity was assessed with Christiansen uniformity coefficient (UCC) (Christiansen, 1941) and compared to ASABE EP458 standards (ASABE EP458, 1999).

$$\text{UCC} = 1 - \frac{\overline{\Delta q}}{\bar{q}} \tag{4}$$

$\bar{q}$ and $\overline{\Delta q}$ being respectively average emitter flow and mean deviation of emitter flow from average.

2.4 Assessment of yield and water productivity performance

An experiment was conducted in a farmer's field in South-west Benin (latitude 6°24′27″ North, longitude 1°52′55″ East, altitude 69 m) in 2015 (January 3 – March 13) and repeated in 2016 (January 17 – March 25). It confronted the bamboo system to conventional plastic-drip and traditional watering can systems (Fig. 2), and also served as demonstration to ease spreading of the new technology.

The experimental design (Fig. 3) was a three-plot randomized block with three replications. Irrigation system was the treatment whose variants were the three above-mentioned irrigation systems. Plots were 12 m^2 (2.4 m x 5 m) and bordered with bricks to insure stability and prevent run-off from can plots.

A Basic Weather Station (BWS200, https://www.campbellsci.eu/bws200) was installed on the site (Fig. 3) coupled to a rain gauge, and provided hourly data to calculate evapotranspiration. These data are *Relative Humidity* (%), *Dewpoint* (Celsius), *Wind Speed* and *its maximum* (Meters per

Second), *Wind Direction* (Degrees) and *its Standard Deviation*, *Total Rainfall* (millimetres), *Total Wind Run* (Metres), *Air Temperature* (Celsius) and *Solar Radiation* (Watts.m^{-2}) and *Barometric pressure* (Millibars). Soil samples were taken at the beginning of the experiments and analysed at the Soil Sciences laboratory of the University of Abomey-Calavi, Benin. Results (table 1) show that plot-soils are sandy loam (according to USDA soil textural classification system) and rich in essential nutrients. NADIRA F1, extra-early tomato (*Lycopersicon esculentum* Mill.) variety was transplanted at 0.6 m x 0.6 m spacing and no mineral fertilizer was applied during cultivation, to clearly see the effect of irrigation treatment on crop yield and water productivity. Pesticides were used when necessary for pest control, and weeding was done manually.

Figure 2. Irrigation systems compared during the field test

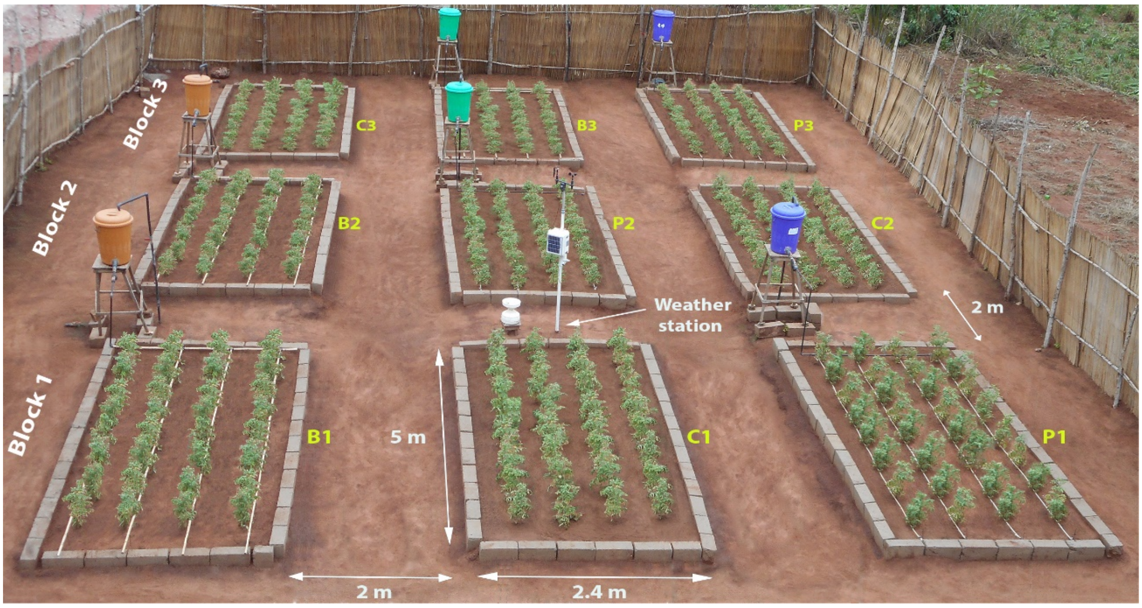

Figure 3. Experimental design

NB: For yield and water productivity tables and figures, first index is for treatment and second for season.

Table 1. Soil characteristics in experiment plots

Season	System	Plot	Silt (%)	Clay (%)	Sand (%)	C/N	N (%)	P (ppm)	K+ (meq/100g)	pH water
1	Bamboo	1	6.59	13.61	79.17	9.43	0.07	80.59	0.71	6.42
		2	4.52	14.69	80.51	9.5	0.06	80.53	0.77	6.31
		3	4.27	17.13	78.1	9.43	0.07	87.99	0.76	6.31
	Plastic	1	2.9	15.9	80.75	9.14	0.07	89.14	0.79	6.45
		2	6.34	13.37	79.7	8.29	0.07	81.63	0.71	6.43
		3	3.41	17.57	78.11	9	0.07	84.5	0.71	6.47
	Can	1	4.98	14.48	80.52	9	0.07	80.96	0.77	6.3
		2	4.54	15.54	79.19	9.17	0.06	86.97	0.78	6.42
		3	5.66	13.25	80.18	9.29	0.07	88.21	0.79	6.2
2	Bamboo	1	4.78	13.94	80.67	8	0.07	83.57	0.77	6.26
		2	5.69	15.92	78.14	9.14	0.07	83.47	0.74	6.25
		3	5.56	15.2	78.85	7.86	0.07	83.29	0.74	6.27
	Plastic	1	7.81	14.51	78.39	7.86	0.07	85.82	0.73	6.44
		2	4.99	13.74	80.61	8	0.07	84.35	0.75	6.37
		3	5.45	15.52	79.72	9.5	0.06	87.08	0.75	6.4
	Can	1	3.55	16.97	78.59	11	0.06	85.3	0.77	6.35
		2	4.73	16.55	78.26	9.43	0.07	85.43	0.72	6.43
		3	2.42	17.4	79.87	9.33	0.06	82.03	0.71	6.44

Plots were harvested at 69 days after transplanting (DAT) and fresh yields determined. Dry yields were then considered 15% of fresh yield, as from FAO (http://www.fao.org/nr/water/cropinfo_tomato.html). Water productivity was calculated with respect to gross irrigation as follows:

$$WP_I = (\text{Dry yield (Kg/ha)})/(\text{Gross irrigation } (m^3/\text{ha})) \quad (5)$$

Irrigation was applied daily at 5:30 p.m. For can plots, the amounts were set according to farmers' practice. For drip plots, net irrigation requirements were first determined from crop evapotranspiration (calculated according to FAO concept; FAO Irrigation and Drainage Paper 56) and rainfall (capillary rise was not relevant due to deep groundwater; 36 m). Next, the theoretical gross irrigation was calculated from net irrigation and estimated application efficiency (90%), and the corresponding irrigation duration determined using the dripper discharge. The system was then opened and left to work till the end of the irrigation duration, and application of the expected gross irrigation cross-checked by volume change in the irrigation tank, calculated from water level observations.

Crop evapotranspiration was calculated using the dual-crop coefficient (Allen *et al.*, 1998) which separates transpiration (productive component) from evaporation (unproductive component). $K_{cb\ (Tab)}$ values were as follows: 0.2 (initial phase), linearly increasing from 0.2 to 1.1 (development phase), 1.1 (mid-season phase) and linearly decreasing from 1.1 to 0.75 (late-season phase).

2.5 Statistical analysis

STATA 13.0 was used for analysis, with 5% significance level. For hydraulics and uniformity performance, t-test was used for comparisons to thresholds. For yield and water productivity performance, one-way analysis of variance (ANOVA) was performed to determine the effect of irrigation treatment on fresh yield and water productivity.

3. RESULTS AND DISCUSSION

3.1 Inherent variabilities in hydraulics

Emitter flow variations caused by inherent variabilities in hydraulics (i.e. the bamboo material, emitters' precision and emitter plugging) are shown in Figure 4.

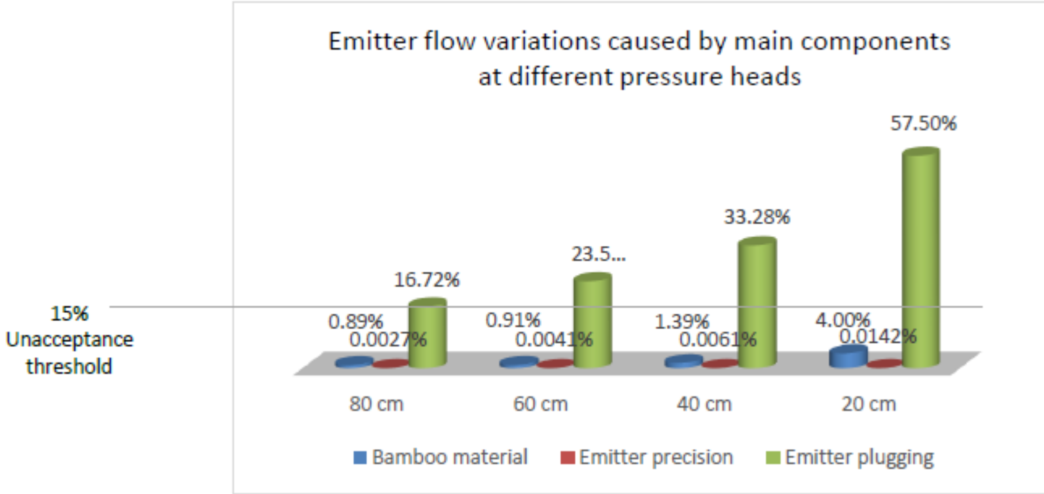

Figure 4. Inherent variabilities in hydraulics at different pressure heads

Results show that flow variations due to bamboo material and emitters precision are excellent at four pressure heads, whereas flow variations due to emitter plugging kept unacceptable overall. Emitter plugging is then the strongest factor causing emitter flow to vary in the bamboo system. Emitter plugging has been proved to be a major problem in micro-irrigation systems in general (Nakayama and Boman, 2007). Several authors studied its effect on emitter flow variation, and most came to the conclusion of an adverse correlation. Indeed, after many field studies, Pitts *et al.* (1996) showed that emitter plugging can be the major cause of emitter flow variation within a micro-irrigation system. Wu (1993) and Wu *et al.* (2007) were more affirmative and pointed plugging as not a possible cause, but the most significant factor affecting emitter flow uniformity. Its consequence is a direct adverse effect on water distribution efficiency and useful life of drip systems (Wu *et al.*, 2007), even when plugging percentage is small (Bralts *et al.,* 1981). Emitters plugging depends on their sensitivity, position on lateral and internal factors (physical, chemical and biological hazards) (Ravina *et al.*, 1992). In the case of the bamboo system, internal factors are irrelevant, as tap water was used for the test. Plugging of emitters is then essentially due to their position on the lateral and their sensitivity, related to flow velocity and passageway size. But passageway size of the hand-made emitters was large enough, making flow velocity the only plugging inducer. Flow velocity at emitter positions may have varied due to singularities in bamboo internodes, and junctions as well. Bamboo internodes used to construct laterals were from culms harvested in different ecological areas. This resulted in imperfect uniformity regarding straightness, sectional shape and inner roughness, even though inner diameters were the same. Thus, the solution to get uniform internodes and reduce emitter flow variations due to flow velocity is to construct pipes wit bamboo internodes coming from a same and unique shrub. This requires cultivation of bamboo in controlled and uniform environment.

3.2 Emitter flow uniformity

Emitter flow uniformity in the bamboo system is shown in Figure 5. Results show that emitter flow uniformity in the bamboo system is acceptable but becomes poor at 20 cm pressure head. Pressure head being directly proportional to water flow velocity, this means water flow velocity in the system at 20 cm head varies too much from an emitter position to another. The reason is, as identified previously, that singularities in bamboo internodes and junctions are very relevant at 20 cm. Getting a good uniformity would then mean either reducing these singularities (by using more identical bamboo internodes) or running the system at higher pressure heads (which would require high, strong and costly tank-holding structures). The first option seems easier and requires just that bamboo segments come from a uniform shrub. The second is more difficult and would reduce the potential of this system to be up-scaled to larger farm sizes.

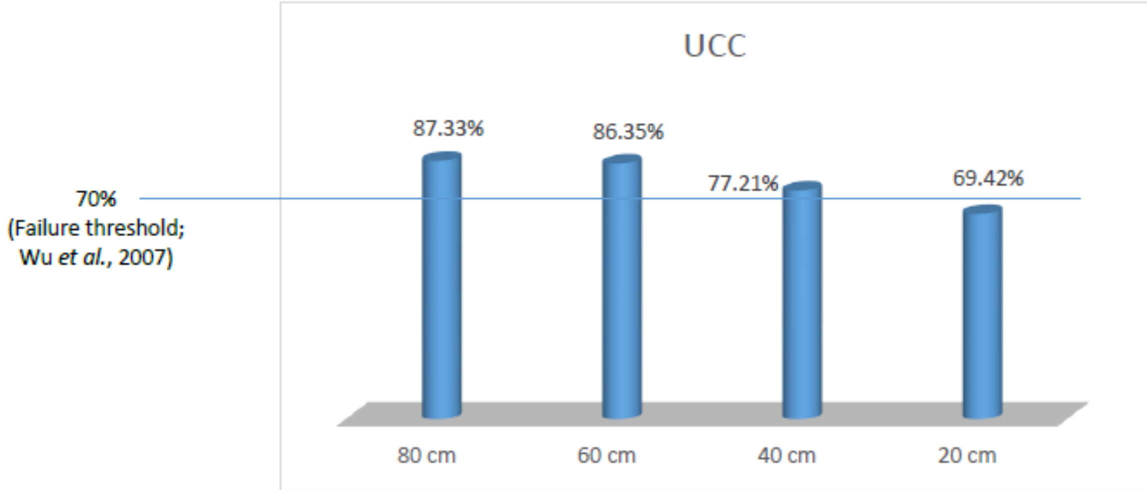

Figure 5. Emitter flow uniformity at different pressure heads

3.3 Yield and water productivity performance

Crop evapotranspiration (as a whole, as well as split in evaporation and transpiration) and gross irrigation amounts of two cropping seasons are shown in Table 2.

Table 2. Evapotranspiration, Evaporation, Transpiration and Gross irrigation amounts per irrigation treatment and per cropping season

Season	**Treatment**	**Evapotranspiration** (mm)	**Evaporation** (mm)	**Transpiration** (mm)	**Gross irrigation** (mm)
S1	Bamboo-drip	194.6	5.1	189.4	228.1
	Plastic-drip	194.6	5.1	189.4	226.1
	Watering can	249.2	59.8	189.4	449.2
S2	Bamboo-drip	199.2	5.5	193.7	228.4
	Plastic-drip	199.2	5.5	193.7	227.9
	Watering can	258.4	64.8	193.7	449.2

Intra-seasonal yields and water productivity per plot and per irrigation treatment are presented in Table 3.

Table 3. Intra-seasonal yields and water productivity per irrigation treatment

Season	**Treatment**	**Dry yield** (Kg.ha^{-1})	**WPi** (Kg.m^{-3})	**Increase of WPi**, as compared to the reference situation (i.e. the can treatment)
S1	BS1	636.5	0.279	99 %
	PS1	627.9	0.278	98 %
	CS1	630.1	0.14	-
S2	BS2	630.8	0.276	85 %
	PS2	624.2	0.274	83 %
	CS2	671.7	0.15	-

Dry yield and water productivity were compared within and between irrigation treatments and cropping seasons, and results presented in Tables 4 and 5.

Table 4. Intra-seasonal comparison of yield and water productivity between treatments

Performance factor	Season	Compared	F	Prob > F
Dry yield (Kg.ha^{-1})	S1	B vs C vs P	0.03	0.9743
		B vs C	-6.38889	1
		B vs P	-8.61111	1
		P vs C	-2.22222	1
	S2	B vs C vs P	3.06	0.1215
		B vs C	40.8333	0.292
		B vs P	-6.66667	1
		P vs C	-47.5	0.188
WPi (Kg.m^{-3})		B vs C vs P	8.87	(0.0162)**
	S1	B vs C	-0.074325	(0.028)**
		B vs P	-0.004426	1
		P vs C	0.069899	(0.037)**
	S2	B vs C vs P	19.26	(0.0024)**
		B vs C	-0.056735	(0.004)**
		B vs P	-0.003346	1
		P vs C	0.053388	(0.006)**

Note: ** Highly significant; * Significant

Table 5. Inter-seasonal comparison of yield and water productivity per irrigation treatment

Performance factor	Compared	F	Prob > F
Dry yield (Kg.ha^{-1})	BS1 vs BS2	-5.69444	1
	CS1 vs CS2	41.5278	1
	PS1 vs PS2	-3.75	1
WPi (Kg.m^{-3})	BS1 vs BS2	-0.010526	1
	CS1 vs CS2	0.007064	1
	PS1 vs PS2	-0.009446	1

First observation is that yields are low overall (Table 3), what can be justified by the absence of mineral fertilization during cultivation and the low planting density applied. A slight pruning was also performed during cultivation to improve plants' health, but it lead to a lesser stem density and fruits number per plant. Another possible yield reduction factor is heat stress caused by the relatively high air temperature (Fig. 6), specifically during harvest index development.

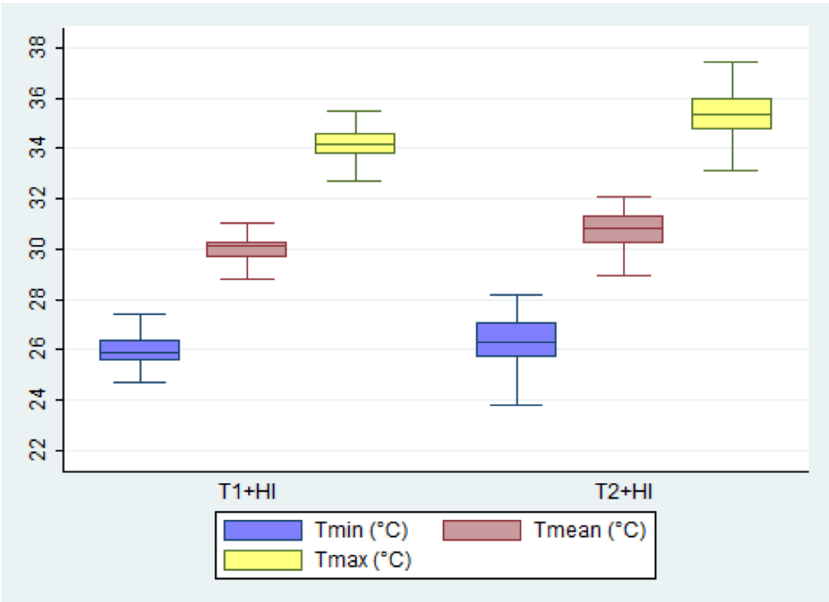

Figure 6. Air temperature during harvest index development (T1+HI = Season 1; T2+HI = Season 2)

High temperature induced high transpiration and abortion of a few flowers. Pollination failure and spikelet sterility also could have happened to a little extent, resulting in a relatively lower fruit size and yields. The adverse effect of high temperature on tomato yield was confirmed by Adams *et al.* (2001) in tropical and sub-tropical parts of the world where they observed respectively 18 and 17% yield reduction at mean temperatures of 26°C and 29°C respectively, as compared to 22°C and 25°C. Zhang *et al.* (2008) also observed important yield decrease (46.1%) at a day temperature of 35°C versus 25°C.

Second observation is that yields are similar between irrigation treatments and between cropping seasons (Tables 4 and 5), which shows that the bamboo system successfully competed with both conventional plastic-drip and watering can systems, regarding good soil moisture condition. Indeed, availability of adequate soil moisture at critical stages of the plant cycle optimizes cell metabolic processes and increases the effective absorption of soil mineral nutrients. As a consequence, any degree of water or aeration stress may produce deleterious effects on plant growth and yield. Too low irrigation frequencies make the root zone too dry (El-Hendawy and Schmidhalter 2010), whereas too high frequencies create excessive soil water content and oxygen limitation, as application rate exceeds root extraction rate. Oxygen limitation in the root zone creates hypoxia paradox (Bhattarai *et al.*, 2005) and impedes uptake of water and nutrients by the roots. Under severe conditions, it leads to the loss of membrane integrity, indiscriminate salt movement into the plants, salt accumulation and subsequent injury to the leaves and to the whole plant (Barrett-Lennard, 2003). By showing similar yield performance as the conventional plastic-drip system, the bamboo system has certainly favoured a well-aerated root zone and avoided deficit or excess root-zone water content.

Third observation is that, due to low overall yields, irrigation water productivity is also low overall (0.276 $Kg.m^{-3}$ and 0.145 $Kg.m^{-3}$ for drip and can treatments respectively), compared to the common average of 1.3 $Kg.m^{-3}$ determined by Battilani (2006) in climates of high evaporative demand and low canopy cover, with frequent wetting of exposed soil surface by rain or irrigation. Yet, compared to the traditional can system, the bamboo system significantly increased water productivity by 99% the first season, and 85% the second season (Table 3). This in accordance to expectations, since water supply by the bamboo system is targeted, reducing losses via evaporation and deep percolation, without negatively affecting yields.

Yield and irrigation water productivity of the bamboo system could be improved by optimizing its layout and combining practicing deficit irrigation or partial root drying technique. Half the root-zone under this system would then be irrigated at less than the maximum crop evapotranspiration (in the case of deficit irrigation), creating some minor stress at appropriate growth and development stages. For partial root drying technique, only one side of the root-zone would be irrigated, creating a drying which would affect biomass and not yield, i.e. trigger a continuous production of sufficient amounts of root-based chemical signals, hence reducing stomatal conductance and leaf expansion without significantly reducing yields. In processing tomatoes, deficit irrigation proved to save water (Battilani *et al.*, 2000). Partial root drying was tested by Kirda *et al.* (2004) in greenhouse grown tomatoes and saved 50% of the irrigation water with only a marginal yield reduction. Zegbe *et al.* (2004) also reported 70% water productivity in tomato fields with partial root drying technique, compared to full irrigation.

3. CONCLUSION

The bamboo-drip system is workable and can be improved. Its laterals and emitters have excellent hydraulic properties, and emitter flow variation is essentially due to emitter plugging. Emitter plugging can be reduced by improving uniformity of the bamboo segments used to construct pipes, or run the system at higher pressure heads. This will also improve flow uniformity in the system as a whole. Yield and water productivity performance of the bamboo system are interesting overall. Yield performance was similar to those of conventional plastic-drip and watering can systems in both cropping seasons. Water productivity performance was similar to that of the plastic-drip system within and between seasons, and 99% and 85% higher than that of the can system in seasons 1 and 2 respectively, thanks to a lower gross irrigation amount. Yet, the bamboo system could not unfold its full potential, due to the absence of mineral fertilization and the low planting density applied. Yield and water productivity performance of the bamboo system can be improved by optimizing its design, using it in deficit mode or practicing partial root drying technique. Time-series studies are being planned to determine other behaviours and characteristics of the system, but yet, it holds promises to enable a more productive use of water at small scale and increase incomes at household level, culminating in a better economy in rural and peri-urban West-Africa.

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