Hydraulic and clogging characteristics of Moistube irrigation as influenced by water quality

Edwin Kimutai Kanda, Tafadzwanashe Mabhaudhi and Aidan Senzanje

ABSTRACT

Irrigation consumes approximately 70% of total freshwater use worldwide. This necessitates the use of efficient irrigation methods such as micro-irrigation. Moistube irrigation (MI) is a new subsurface irrigation technology where the water emits from a semi-permeable membrane of the Moistube at a slow rate depending on the applied pressure and soil water potential. There is currently limited information on the performance of Moistube tapes with respect to discharge as a function of pressure or water quality. The aim of this study was to determine the flow characteristics of Moistube tapes as a function of pressure and the effect of suspended and dissolved solids on the emission characteristics. The pressure–discharge relationship was determined within a range of 20 kPa and 100 kPa. The clogging of the Moistube was determined using water containing low, moderate and high concentrations of suspended and dissolved solids at 20 kPa and 30 kPa. The results indicated that the Moistube discharge follows a power function with the applied pressure. The discharge decreased linearly over time because of clogging. Suspended solids had a more severe clogging effect on Moistube than dissolved solids. The results of this study should help in the design, operation and maintenance of MI systems.

Key words | dissolved solids, low-pressure irrigation, micro-irrigation, nanoporous pipe, subsurface irrigation, suspended solids

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INTRODUCTION

Irrigation constitutes approximately 70% of the world's freshwater use (Kulkarni 2011). Consequently, irrigated agriculture is under pressure to increase crop water productivity. The use of subsurface irrigation helps to save water by minimizing unproductive water loss components such as surface runoff, soil evaporation and percolation. Despite minimal water losses in subsurface drip irrigation, there is still a problem of nutrients and water leaching, especially in light-textured soils (Cote *et al.* 2003). In an attempt to address this problem, a new subsurface irrigation technology was developed which utilizes a semi-permeable membrane to supply water continuously to the plant at a slow rate (Zhang *et al.* 2012; Lyu *et al.* 2016). Moistube irrigation (MI) is a new irrigation technology which is like drip irrigation. However, instead of emitters, water emits from the semi-permeable membrane of the Moistube tape depending on the applied pressure and the soil water potential of the surrounding soil. The main distinguishing feature of Moistube is its ability to supply water, in the absence of applied pressure, in response to the soil water potential (Zhang 2013).

The main types of porous irrigation pipes, based on the pipe material, include porous clay pipes (Gupta *et al.* 2009) and flexible porous pipes made of rubber and polyethylene (Amin *et al.* 1998; Teeluck & Sutton 1998; Liang *et al.* 2009). These can further be classified based on the size of the emission pores as microporous pipes (Amin *et al.* 1998; Teeluck & Sutton 1998) and nanoporous where Moistube

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tapes belong. These pipes function as both conveyance and emission of the irrigation water. Porous pipe irrigation can be categorized as line-source trickle irrigation where the water is emitted over the entire length through closely spaced emission devices, and whose wetting pattern is a continuous strip.

Porous pipes have been applied in various parts of the world, particularly in arid and semi-arid areas. They are popularly marketed as 'leaky pipe' and 'soaker hose' (Yoder & Mote 1995; Janani *et al.* 2011). Isoda *et al.* (2007) found that the water use efficiency (WUE) of porous pipes was the same as that of drip irrigation. For tomatoes grown in greenhouses in China, Xue *et al.* (2013) found that MI had 13% higher WUE than drip irrigation while Lyu *et al.* (2016) found water savings of 38% higher in MI compared to drip irrigation with mulch. The higher WUE and water savings in MI compared to conventional drip can be explained by the fact that the former supply water is at 80–90% of field capacity, (Zhang *et al.* 2012) which is a form of deficit irrigation and thus improves crop water productivity and WUE. Other advantages of MI include energy savings, low operation costs and minimal percolation losses (Lyu *et al.* 2016).

Design and operation of an irrigation system requires knowledge of the hydraulic characteristics. Porous pipes made of elastic and flexible materials such as rubber exhibit variable permeability with respect to the applied pressure, which in turn affects its emission characteristics (Liang *et al.* 2009). The flow in a porous pipe decreases with time until a stable value is reached (Teeluck & Sutton 1998; Liang *et al.* 2009). There is a need for research on discharge characteristics of irrigation pipes with nanopores as emission devices. The use of nanotechnology in the manufacture of porous irrigation pipes may help in achieving partial desalinization (Madramootoo & Morrison 2013), which is useful in the utilization of saline water in irrigation.

Water for agricultural use comes from various sources such as reservoirs, municipal water supply systems, groundwater and recycled wastewater. These water sources have a varying degree of quality which may pose problems to subsurface irrigation systems in terms of clogging of emission devices. Surface water sources contain impurities such as sand, silt and clay, and biological components like algae. Groundwater generally has high concentrations of dissolved ions such as calcium, iron, manganese, magnesium and carbonates, among others. Depending on the source and method of treatment, recycled wastewater contains organic matter, suspended solids, dissolved ions and microorganisms.

Clogging is one of the serious problems in micro-irrigation systems, discouraging users and resulting in the substitution of the system with less efficient irrigation methods (Nakayama *et al.* 2007). Emitter clogging can be classified as physical clogging due to suspended solids and organic materials, chemical clogging due to precipitates of dissolved solids and biological clogging due to algae and bacteria (Tripathi *et al.* 2014). Besides water quality, the type of emitter also determines the degree of clogging where pressure-compensating emitters have a higher resistance to clogging than laminar flow-type emitters and labyrinth-type emitters with a turbulent flow (Liu & Huang 2009). Clogging of emitters leads to poor water distribution, hence limiting plant growth (Zhang *et al.* 2017) and thereby negatively affecting crop yields.

Despite the continued use of porous irrigation pipes, especially in the arid and semi-arid areas, there is little information on their clogging characteristics. Xie *et al.* (2014) found that irrigation water containing soil particle sizes of between 37 μm and 74 μm can clog Moistube pores. No study has been reported on the effect of dissolved solids on the clogging of Moistube. Clogging mechanisms vary with water quality and the operational parameters and are, therefore, specific to a given site.

The objective of this study was to determine the discharge characteristics of Moistube as a function of operating pressure. The study also involved the determination of the effect of suspended solids and dissolved solids on the clogging characteristics of Moistube. The effect of dissolved solids on Moistube discharge is of primary importance in cases where groundwater or saline water are used for irrigation. This would help in understanding the design, operation and maintenance requirements of MI systems.

METHODOLOGY

Pressure–discharge relationship

To determine the pressure–discharge relationship, a laboratory experiment was set up to measure the discharge from the Moistube under a pressure range of 20 kPa to 100 kPa at intervals of 10 kPa. There is no guideline on the length required for testing the discharge characteristics of porous pipes. In this study, the length of the Moistube used was 1 m. The length was kept small so that friction losses were minimized (Kirnak *et al.* 2004). The discharge was obtained by measuring the volume of water collected over 15 minutes using a 1,000 mL graduated cylinder.

The discharge as a function of pressure was represented by a power function illustrated in Equation (1) (Keller & Karmeli 1974):

$$q = k_p h^x \quad (1)$$

where q = flow rate (L/hr/m), k_p = emitter constant, h = operating pressure (m) and x = is emitter exponent.

The power relationship in irrigation emitters helps in the characterization of the flow regime using the value of the exponent where a value of 1 indicates laminar flow and 0.5 shows a fully turbulent flow. The intermediate values represent a partially turbulent flow (Clark *et al.* 2007) and values below 0.5 indicate pressure compensating properties.

Porous irrigation pipes have pores whose sizes and distribution vary randomly and thus, the emission along the pipe will vary (Yoder & Mote 1995). The emission uniformity from the Moistube was determined by measuring the flow from 20 cm segments of the lateral over a length of 1 m. This was replicated five times. The Moistube lateral was laid horizontally but the PVC gutter sloped gently (1%) to allow for the collection of water from the segments. The experimental set-up is shown in Figure 1. The performance was evaluated using the coefficient of variation (CV) according to Equation (2) (Liang *et al.* 2009):

$$CV = \frac{S}{\bar{q}} \times 100 \quad (2)$$

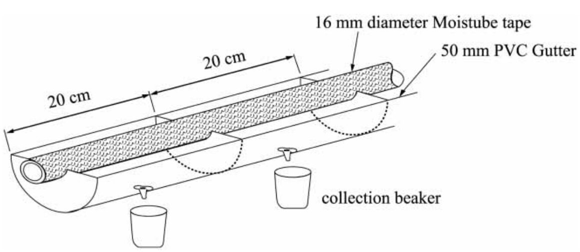

Figure 1 | Setup for the determination of the coefficient of variation.

where CV = manufacturer's coefficient of variation (%), S = standard deviation of discharge (L/hr/m) and $\bar{q}$ = average discharge (L/hr/m).

The CV expressed in Equation (2) is as a result of emitter design, the material used and the precision of the manufacturing process (Capra & Scicolone 1998).

Emission characteristics due to clogging

The effect of clogging due to the presence of suspended particles in irrigation water was determined by measuring the flow from Moistube at 20 and 30 kPa using water containing silt and clay particles. Soil passing through a 125 μm sieve was added to tap water to achieve a concentration of 25 (TS1), 75 (TS2) and 150 mg/L (TS3) which have a low, medium and severe clogging risk, respectively (Nakayama & Bucks 1991), as indicated in Table 1. Clogging due to dissolved solids was determined by adding equal proportions of calcium chloride, magnesium sulphate and sodium bicarbonate to give concentrations corresponding to low (TD1), moderate (TD2) and severe clogging risk (TD3), respectively, as illustrated in Table 1.

The experimental set-up is illustrated in Figure 2. The experiment consisted of a 260 L tank situated in a stand with two platforms at 2 m and 3 m. This allowed for measurement at 20 kPa and 30 kPa. The set-up also consisted of 50 cm length Moistube replicated four times in a manifold arrangement. The spacing between the laterals was 30 cm. The discharge was measured by collecting water using 1,000 mL graduated cylinders for 15 minutes every 24 hours for a period of 14 days. To ensure adequate mixing and suspension of the soil particles, a low-head submersible pump was placed at the bottom of the tank.

Table 1 | Experiment treatments

Treatment	Clogging material	Clogging risk
T0	Tap water	Control
TS1	Suspended solids (25 mg/L)	Low
TS2	Suspended solids (75 mg/L)	Moderate
TS3	Suspended solids (150 mg/L)	Severe
TD1	Dissolved solids (250 mg/L)	Low
TD2	Dissolved solids (1,000 mg/L)	Moderate
TD3	Dissolved solids (2,500 mg/L)	Severe

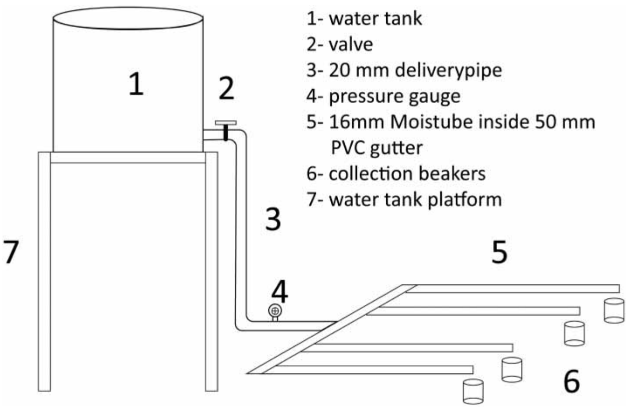

Figure 2 | Experimental set-up.

The water quality in the tank was monitored by testing periodically over the duration of the experiment to ensure that it remained within the set limits (little, moderate and severe clogging risk) and any variation adjusted accordingly. The parameters tested were total suspended solids (TSS), pH, temperature (T), electrical conductivity (EC) and total dissolved solids (TDS), which were analysed using a portable handheld TSS meter from HACH industries (TSS resolutions of 0.1 at 10–99.9 g/L and 1 at greater than 100 g/L), and HI98129 combo tester for pH/EC/TDS/temperature from Hanna Industries (resolutions of 0.01 pH, 1 μS/cm, 1 ppm, 0.1 °C). The water quality characteristics are shown in Table 2.

The effect of suspended and dissolved solids was determined by examining relative discharge over the duration of the experiment. The relative discharge was computed as in Equation (3):

$$q_{rel} = \frac{q_i}{q_0} \times 100 \quad (3)$$

where q_{rel} = relative mean discharge (%), q_i = average discharge (L/hr/m) at time t ($0 \le t \le 336$) hrs and q_0 = average initial discharge obtained at the beginning of the experiment (L/hr/m). The average initial discharge was the mean initial discharge of the four replicates at the beginning of the experiment.

Statistical analysis

The data were analysed using SPSS version 24. Analysis of variance was carried out and the separation of means done by the least significant difference (LSD). The analysis was conducted at 5% significance level.

RESULTS AND DISCUSSION

Pressure–discharge relationship

The discharge from Moistube under varying pressure can be represented by a power function ($R^2 = 0.98$) as illustrated in Figure 3. The average discharge varied from 0.24 L/hr/m at 20 kPa to 1.73 L/hr/m at 100 kPa.

The relationship between discharge and pressure can be expressed by Equation (4):

$$q = 0.1116h^{1.1948} \quad (4)$$

The exponent value greater than 1 indicates that MI is sensitive to pressure changes which is similar to non-pressure compensating drip emitters, and thus the length of laterals should be short (Kirnak *et al.* 2004). The value

Table 2 | Mean water quality characteristics

Treatment	pH	TDS (mg/L)	T (°C)	EC (μS/cm)	TSS (mg/L)
T0	7.8 ± 0.5	31.7 ± 1.6	19.2 ± 2.0	65.0 ± 2.1	
TS1	7.6 ± 0.2	32.0 ± 1.2	19.2 ± 0.6	64.8 ± 1.9	25.0 ± 4.9
TS2	7.4 ± 0.1	34.4 ± 2.9	19.7 ± 0.5	70. 0 ± 4.1	73.2 ± 4.8
TS3	7.5 ± 0.1	37.2 ± 1.6	21.4 ± 0.7	74.6 ± 3.0	147.8 ± 13.9
TD1	7.2 ± 0.3	269.2 ± 14.0	17.3 ± 2.1	531. 4 ± 27	
TD2	6.9 ± 0.3	1,036.1 ± 218.6	15.3 ± 1.1	2,060.8 ± 434.1	
TD3	7.3 ± 0.1	2,480.8 ± 68.0	18.8 ± 0.8	4,678.5 ± 460.4	

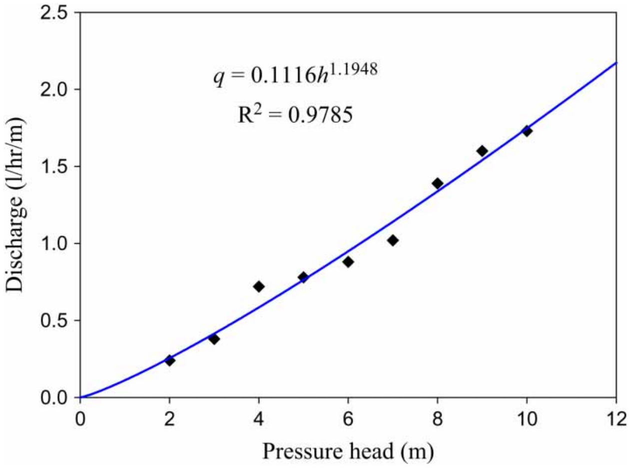

Figure 3 | Discharge–pressure relationship.

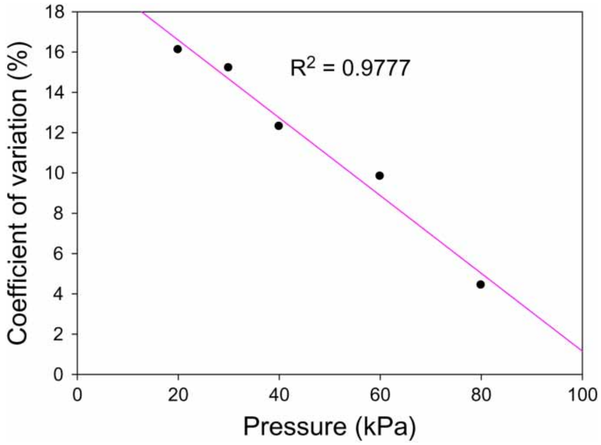

Figure 4 | Emission variation along lateral length at varying pressure.

of the exponent in Equation (4) shows that the flow regime is laminar (Clark *et al.* 2007).

The high sensitivity of discharge with pressure variation in MI, as indicated by the exponent value greater than 1, is consistent with studies carried out for porous irrigation pipes (Amin *et al.* 1998; Liang *et al.* 2009; Pinto *et al.* 2014).

From Equation (4), there will be no discharge from the Moistube at zero pressure. As explained by Zhang (2013), the flow of Moistube varies with the soil water potential and the system pressure. Therefore, in the absence of pressure, the discharge will only occur when there is suction from the surrounding soil.

Emission uniformity along the lateral

The CV ranged from 4.4% to 16.1% (Figure 4) with an average of 11.6% which was within the acceptable range (<20%) for line-source emitters (Teeluck & Sutton 1998). Manufacturing variation is one of the factors that affect the uniformity of an irrigation system. The results of this study demonstrate that acceptable water application uniformity can be achieved with MI if other design factors such as lateral diameter and spacing are implemented correctly. The CV values were better than those found by Teeluck & Sutton (1998) (23.9–58%) and Liang *et al.* (2009) (14.3–48.7%) for porous plastic pipes. Yoder & Mote (1995) found the CV values in 30 cm segments of porous pipes to be within acceptable ranges. As illustrated in Figure 4, the CV decreased linearly ($R^2 = 0.98$) with increasing pressure. This can be attributed to enlargement of pores and increase in the number of active pores which were not emitting at lower pressures. Therefore, MI can be designed and operated at pressures of 50 kPa and 100 kPa where the CV values are less than 10%.

Clogging effect on emission characteristics

Effect of suspended solids

The effect of suspended solids on Moistube discharge, as measured by the relative discharge over time, is illustrated in Figure 5. In some instances, such as for T0 and TS1, the discharge increases slightly in the first 24 hours. This could be attributed to the production of more effective pores as the operation time increased and as the pipe was soaked. There was no significant difference among the discharges for the first 2 days ($p > 0.05$) but it became significant as the time of operation increased ($p < 0.05$) indicating the reduction of discharge because of clogging.

The reduction in discharge from the Moistube followed a relatively linear relationship with R^2 values of 0.95, 0.93 and 0.96 for TS1 (low concentration), TS2 (moderate concentration) and TS3 (high concentration), respectively. The decrease in discharge in Moistube due to clogging is dissimilar with drip irrigation emitters where the rate of discharge declines gradually in the first few days, then drastically in the latter stages.

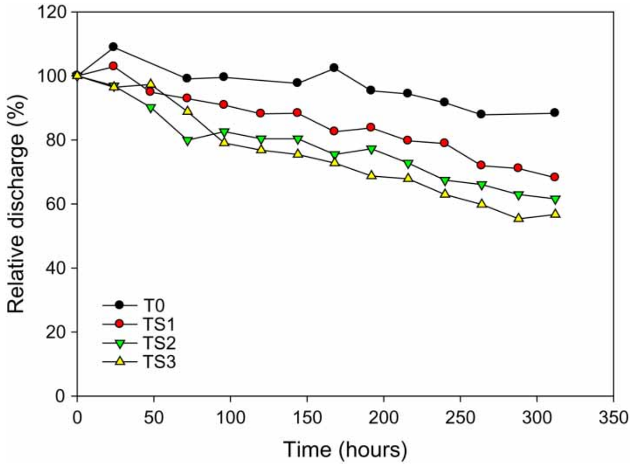

Figure 5 | Relative discharge at 20 kPa.

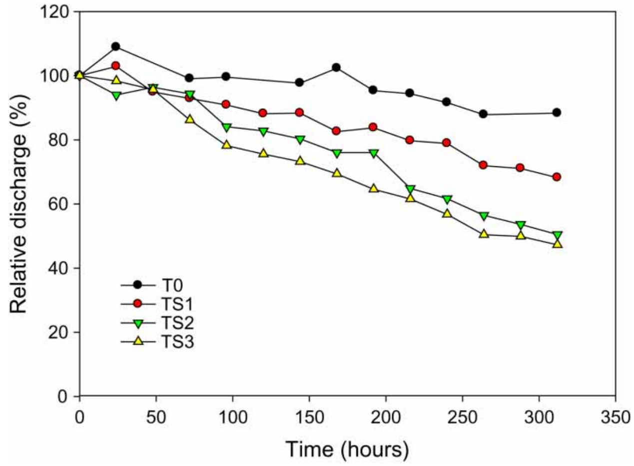

Figure 6 | Relative discharge at 30 kPa.

The difference in reduction of discharge, over the full-time range, was significant between the tap water (T0) and the other concentrations of suspended solids, between TS1 and TS2, and between TS1 and TS3 ($p < 0.05$). However, there was no significant difference between the reduction in discharge between TS2 and TS3 ($p > 0.05$). Capra & Scicolone (2007) explained that suspended solids of about 50 mg/L could be considered as the critical level which contributes to clogging. Taking 25% reduction in discharge (75% relative discharge) as a critical measure of clogging (Niu *et al.* 2013), the Moistube tape could be said to be clogged after 168 hours, 216 hours and 312 hours for TS3, TS2 and TS1, respectively. Although the relative discharge in the control (T0) did not reach critical levels during the entire duration, there was a reduction in discharge, especially after 216 hours. This could be attributed to a higher pH (7.8 ± 0.5) in the tap water (Table 2), which is considered to have moderate clogging effect through accelerated precipitation of dissolved ions. Liang *et al.* (2006) found that tap water, in comparison to distilled water, led to a decrease in emission rates over time from porous irrigation pipes due to clogging. However, Liang *et al.* (2009) found a decrease in emission from porous pipes even when distilled water is used, which was attributed to structural changes in the pipe material.

The relative discharge at 30 kPa is illustrated in Figure 6. The discharge decreased with time and it passed the critical level of 75% after 144 hours, 200 hours and 264 hours for TS3, TS2 and TS1, respectively. The decrease in discharge between all the concentrations were significant except between TS2 and TS3.

The decrease in discharge over time under suspended solids at 30 kPa followed a linear relationship, as in the case with 20 kPa, with R^2 of 0.97 for both TS1 and TS2, and 0.98 for TS3.

The reductions in discharges at the end of the experiment (14 days) were 25.7%, 38.4% and 43.3% at 20 kPa, and 31.8%, 49.5% and 52.7% at 30 kPa for TS1, TS2 and TS3, respectively. The difference between the initial and final discharges was significant for all the treatments except T0 ($p < 0.05$). The reduction in discharge was higher at 30 kPa than 20 kPa. At the higher pressure, the collision of clay and silt particles increases, which in turn creates a coagulating effect and the relatively larger drag force makes the developed flocs unable to escape (Niu *et al.* 2013). Furthermore, at higher pressure, a relatively larger amount of soil particles passes through the Moistube pores because of higher discharge and, consequently, the number of clogged pores is increased.

The difference in clogging characteristics at 20 kPa and 30 kPa for paired respective concentrations was not significant ($p > 0.05$). This implies that pressure had no significant effect on the clogging characteristics due to suspended solids.

Effect of dissolved solids

The effect of dissolved solids on Moistube discharge is presented in Figures 7 and 8 for 20 kPa and 30 kPa,

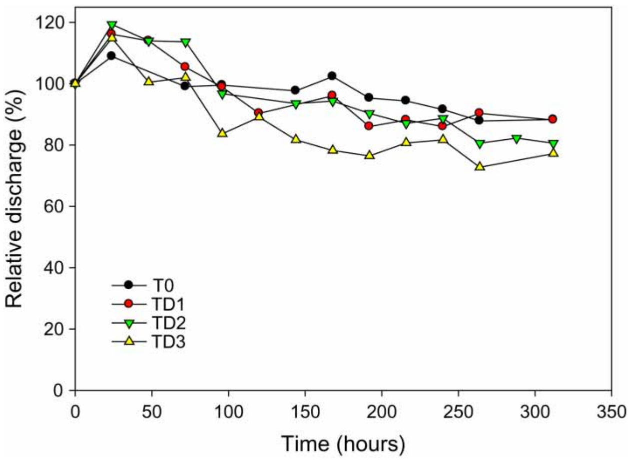

Figure 7 | Relative discharge at 20 kPa.

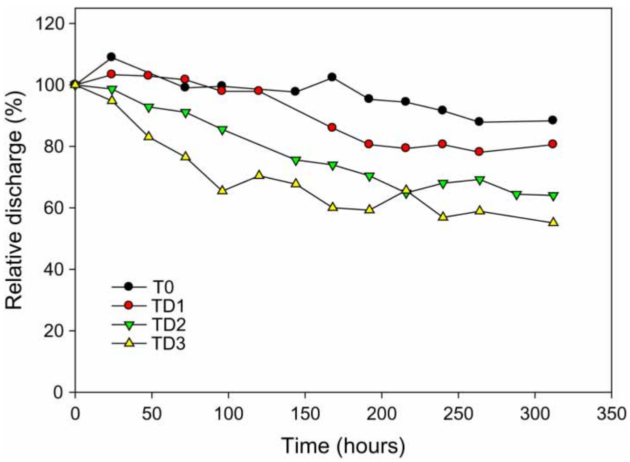

Figure 8 | Relative discharge at 30 kPa.

respectively. The discharge increased slightly after 24 hours, signifying the increase in the number of effective pores as the pipe gets soaked with water. The discharge from Moistube takes a while, especially during low pressures.

There was no significant difference among the concentrations for the first 6 days ($p < 0.05$). This implies that the clogging process had not been initiated. However, from day 7, there were significant differences among the relative discharges, indicating the effect of clogging due to the precipitation of the dissolved salts. The relative discharge was above 75% in all the concentrations at 20 kPa and at TD1 (low concentration) at 30 kPa. The discharge decreased to 55% and 64% for TD3 (high concentration) and TD2 (moderate concentration), respectively, at 30 kPa. There was no significant difference between the initial and final discharges for T0 and TD1 ($p > 0.05$) which signify low clogging levels. However, there was a significant difference between the initial and final discharge for TD2 at 30 kPa and TD3 at both pressures, indicating a clogging effect. There was no significant difference among the relative discharges at 20 kPa ($p > 0.05$). There was a significant difference between T0 (control) and both TD2 and TD1 and between TD1 and TD3 ($p < 0.05$) at 30 kPa. However, the difference was not significant between T0 and TD1, and between TD2 and TD3. Previous studies on clogging of drip emitters indicated that they performed relatively worse than Moistube. Lili *et al.* (2016) found that saline water (EC = 3,560 μS/cm) decreased discharge of some drip emitters to 46% after 126 hours of operation. Similarly, Liu *et al.* (2015) found a reduction in discharge of up to 85% after 35 days of drip irrigation with hard water (water hardness = 500 mg/L) and the primary component responsible for clogging was $CaCO_3$. The possible explanation for relatively lower clogging of Moistube is due to the numerous number of pores per unit surface area. This, therefore, increases the time taken for a significant number to be clogged by the precipitated ions.

Dissolved solids do not cause clogging unless the ions precipitate (Nakayama *et al.* 2007). However, in this study, precipitation was enhanced by the addition of $NaHCO_3$ which upon dissolution frees the CO_3^{2-}, which in turn reacts with Mg^{2+} and Ca^{2+} ions from the dissolved $MgSO_4$ and $CaCl_2$, respectively. Also, the pH level of greater than 7.5 in the tap water helped to accelerate the precipitation process. Dissolved solids clog the porous irrigation pipes when the chemical precipitates flocculate around the emission pores, partially or completely restricting the flow. Lili *et al.* (2016) found that the major chemical compound responsible for clogging of drip emitters was $CaCO_3$.

The variation in clogging characteristics between the two pressures was significant for TD2 and TD3 ($p < 0.05$). This implies that pressure had an effect on the Moistube clogging. This can be explained by the fact that at 30 kPa with moderate to high concentrations, a higher amount of precipitates passes through the Moistube per unit time and some are stuck in the pores since the pressure is not high enough to push them out. However, there was no significant difference in the relative discharge of TD1 between the two pressures. This means that at low concentration of dissolved solids, the effect of pressure is negligible.

The decrease in discharge followed a fair linear relationship at 20 kPa with R^2 of 0.66, 0.79 and 0.72 for TD1, TD2 and TD3, respectively, and a good linear relationship at 30 kPa with R^2 values of 0.86, 0.93 and 0.80 for TD1, TD2 and TD3, respectively.

Multiple analysis of variance indicated that time and concentration were significant factors affecting discharge from Moistube. Discharge decreased with increasing time at varying rates because of clogging by suspended and dissolved solids. There was a significant difference between the relative discharges for suspended and dissolved solids. Suspended solids had a greater effect on clogging than dissolved solids. All the concentrations of suspended solids had a significant effect on the relative discharge while the effect of dissolved solids on the relative discharge was only significant at TD3 ($p < 0.05$). Therefore, water devoid of suspended solids should be used in the MI system. In this regard, filtration systems like those of drip irrigation should be used in the MI system to reduce the effect of clogging.

CONCLUSIONS AND RECOMMENDATIONS

From the findings of this study, the following conclusions can be drawn:

(1) The Moistube discharge increased with increasing pressure. The pressure discharge relationship followed power function with an exponent of greater than 1. Therefore, the flow from Moistube is sensitive to pressure changes.
(2) The manufacturing CV decreased with increasing pressure because of the balancing or evening-out effect. The best operating pressure range for MI is between 50 kPa and 100 kPa where the CV values were less than 10%.
(3) The reduction in discharge ranged from 26% to 53% because of suspended solids and 12% to 45% due to dissolved solids. Moistube laterals were relatively resistant to clogging due to dissolved solids less than 1,000 mg/L. Suspended solids had a significantly higher effect on reduction in Moistube flow than dissolved solids.

Water quality is paramount in the MI system and, therefore, appropriate treatment methods for removal of suspended and dissolved solids need to be used to prevent clogging. Further research needs to be carried out under a wide range of pressures to fully understand the effect of pressure on Moistube clogging characteristics. Long-term clogging tests are needed to determine the effect of suspended and dissolved solids in a typical crop-growing season.

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