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ORIGINAL PAPER

Inhibition of root penetration in subsurface driplines by impregnating the drippers with copper oxide particles

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Abstract Clogging of subsurface drip irrigation (SDI) systems by root penetration into the emitters results in inappropriate water supply, increased replacement rates of SDI systems and increased costs. We found that impregnation of SDI drippers with copper oxide particles inhibits root penetration very significantly. The inhibition of root penetration varied from 24 to 76 % of the control (60–80 % intrusion) depending on the copper oxide concentration of the drippers. The root penetration inhibition was demonstrated at two water flow rates, of 1 and 3.5 l/h, and with new and used drippers after 1750 irrigation hours. Inhibition of root penetration occurred also if sewage water was used. The inhibition of root penetration into drippers was demonstrated with lettuce and tomato plants and reached similar efficacy as compared to the widely used herbicide Stomp® root penetration inhibition treatment. The amount of copper that leached into the water was below detection limit (less than 0.006 ppm). No loss of copper oxide particles was detected in drippers through which 3350 l of water was passed (an amount of water that typically passes in SDI systems during 3–4 years of use), as determined by scanning electronic microscope and X-ray photoelectron spectrum analysis.

Introduction

Subsurface drip irrigation (SDI) is a very efficient irrigation system aimed at ensuring uniform and adequate supply of water to each plant according to its needs. Water is delivered directly to the roots of plants. This method prevents or minimizes evaporation and runoff and is especially useful in places where water is a limited resource.

A significant problem associated with SDI is the clogging of the emitters via root penetration. Roots tend to proliferate in favorable environments where water and nutrients are readily available, and the presence of a constant water and nutrient supply, emanating from the irrigation line emitters, favors root intrusion of the emitters. The root intrusion causes partial or total blockage of the dripper outlet. Depending on the aggressiveness of the root system and the type of the emitters, a number of adjoining emitters can be blocked, and in extreme cases, even a whole lateral, which in turn prevents water supply to downstream emitters.

One way to prevent root penetration is by treating the water or the drippers themselves with an herbicide, for example, with trifluralin (Sheval et al. 2008; Spera et al. 2006). The addition of the herbicide may necessitate an injection pump that releases the herbicide at a prescribed dosage and rate, or alternatively emitters may contain the herbicide. This provides a continuous slow release process of the herbicide as water passes through it. However, herbicide use carries risks that include environmental, ecological and human health effects (Ahemad and Khan 2009; Bernard et al. 2005; Eason et al. 2004). Another possibility of reducing root penetration has been the use of copper. Copper is known to have potent antibacterial, fungicidal and algaecidal properties (Borkow and Gabbay 2005; Murray-Gulde et al. 2002). Copper compounds are widely used today as algaecides and herbicides (Bishop and Rodgers 2012; Borkow and Gabbay 2005), and several soluble copper compounds have been shown to inhibit root elongation (Arduini et al. 1995; Meier et al. 2012). However,

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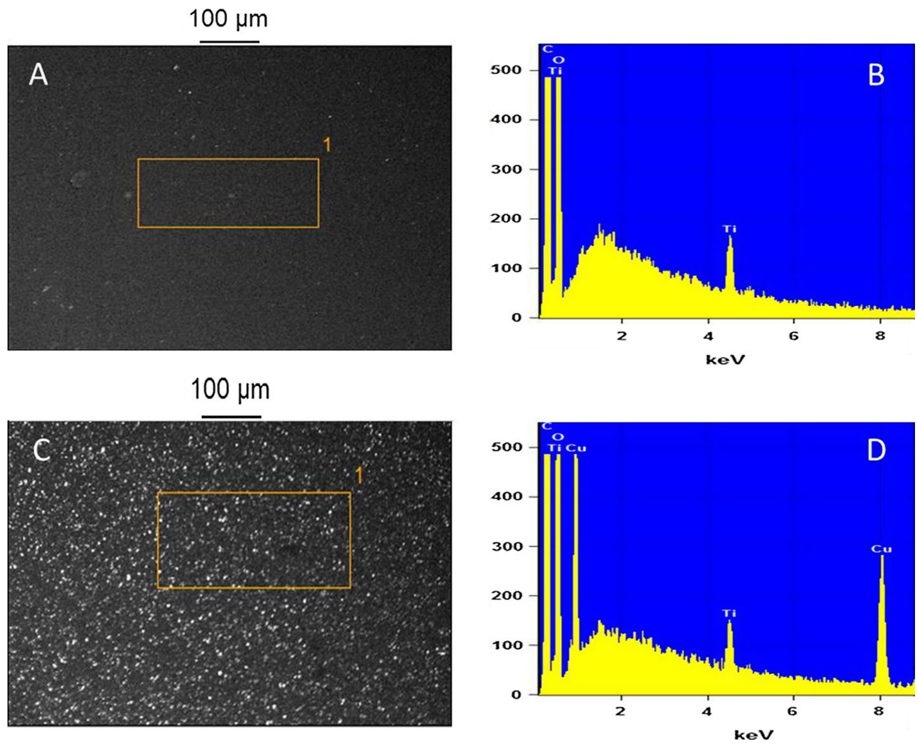

Fig. 1 Scanning electron microscopy (SEM) and X-ray photoelectron spectrum of untreated HDPE (**a**, **b**) and of HDPE containing 5 % (w/w) copper oxide particles (**c**, **d**)

since these are chemicals that readily solubilize in water, they may have adverse environmental effects (de Andrade Waldemarin et al. 2012; Mastin and Rodgers 2000). Thus, non-soluble metallic copper pieces are being introduced in subsurface drip irrigation systems to protect the emitters from root intrusion (http://www.rainbird.com/landscape/products/dripline/XFS.htm).

In the current study, we introduced non-soluble copper oxide particles in subsurface drip irrigation emitter heads and investigated their capacity to reduce root penetration and obstruction of the irrigation systems.

Materials and methods

Introduction of copper oxide particles into emitter heads

We introduced the copper oxide particles into polyethylene by using the published platform technology of introducing copper oxide particles into different polymeric materials (Borkow and Gabbay 2004). As can be seen in scanning electronic microscope pictures and the X-ray spectra analyses in Fig. 1, the copper oxide particles (the white dots seen in Fig. 1c) are homogenously distributed throughout the high-density polyethylene (HDPE) matrix and constitute an integral part of the dripper's head. The concentration of copper oxide particles introduced into the matrix varied between 0 and 40 % weight/weight.

Determination of root intrusion into drippers

Experiments were generally performed as follows unless specified otherwise in the Results section: Individual, 4 m length, 0.5 m width and 0.35 m height, cases with an overall volume of 700 l were used as plots. Except in one case, the number of plots per experiment varied between 12 and 28 plots. The treatment of each plot was randomized. The cases were placed in a greenhouse in Kibbutz Hatzerim, Israel. The soil growth medium consisted of sand and compost at a 7/3 ratio. In each case, two subsurface irrigation lines (DripNet PC™ dripper lines or UniRam™ RC or UniRam™ AS, Netafim) were installed 15 cm below the surface. Each line had 40 drippers. The distance between each dripper was 20 cm, and each dripper flow rate, depending on the experiment, varied between 0.4 to 3.5 l/h. At least four plots per treatment were used, i.e., 160 drippers. A total of 40 plant seedlings of ~3 weeks of age (lettuce or tomato, as detailed in the "Results" section) were planted in each case in two rows, being the distance between each row 20 cm. Until plant establishment (~7 days from seeding), the plants were watered daily by using Coolnet Pro™ mist emitters in addition to the watering regime that varied among experiments as described in Fig. 2. The watering regimes were designed to decrease gradually the amount of water applied in order to develop water stress and promote root intrusion into the drippers. During all experiments, the plants were treated via irrigation with a fertilizer composed of 6:4:4: nitrogen, phosphate and potassium, respectively,

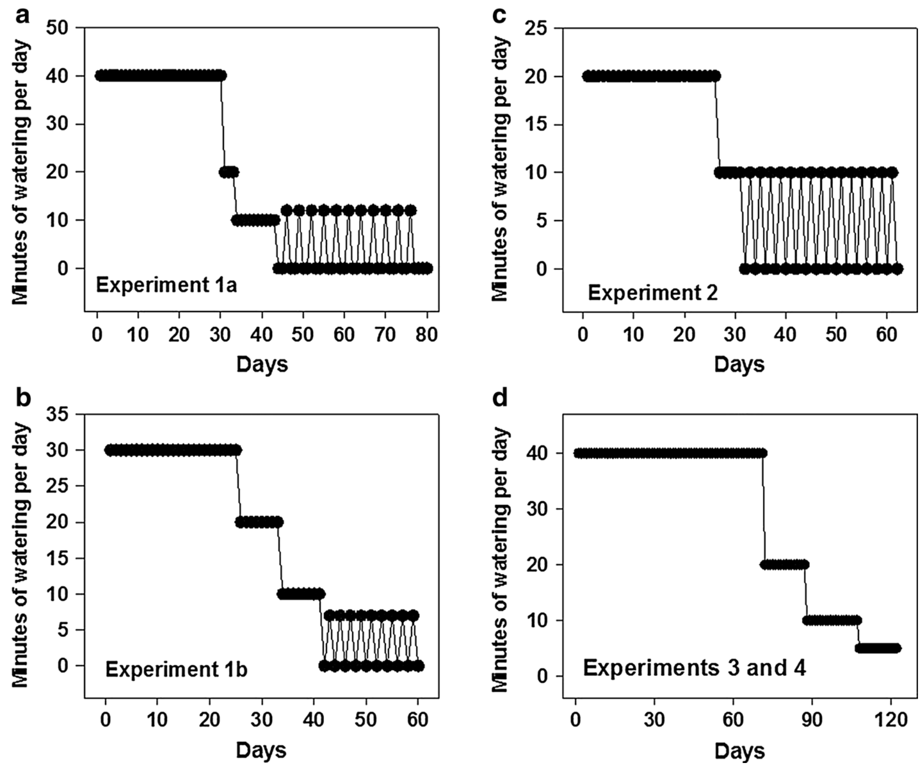

Fig. 2 Watering regimens of the different experiments performed to encourage root intrusion into the drippers

at 1.4 l/m^3 daily application. At the end of the experiments, which varied between 2 and 4 months, the irrigation lines were removed, the drippers exposed and the root intrusion determined.

Determination of copper elution from copper oxide-impregnated drippers

The elution of copper from the copper oxide-impregnated drippers was determined in two different experimental settings. Firstly, the amount of copper eluting from a dripper containing copper oxide was determined by passing 250 ml of tap water through the dripper at a flow rate of 1 l/h. The water passing through the dripper was collected for 15 min. The copper content of the collected 250 ml water, and that present in 250 ml of tap water that was not passed through the dripper, was determined by inductively coupled plasma mass spectrometry (ICP-MS, ARCOS, Spectro GMBH, Germany). Secondly, tap water was passed through a 15-m-long tube containing 50 copper oxide-impregnated drippers placed at a distance of 30 cm for a period of 140 days. A total of 3350 l of water, at a flow rate of 1 l/h, was circulated through the tubing. At the end of the experiment, the drippers were removed from the tubing and the presence of copper on the surface of eight drippers was examined by using scanning electronic microscopy (SEM; Jeol JMS 5410 LV scanning electron microscope, Japan) and the presence of copper coverage was determined by X-ray photoelectron spectrum analysis (Link IV, ISIS, Oxford Instruments, England). Eight copper oxide-containing drippers that were not exposed to water were used as reference.

Results

Prevention of root intrusion

Experiment 1

We first tested the effect on root intrusion into drippers impregnated with two different copper oxide concentrations, 12.5 and 25 % w/w, as compared to the control drippers without copper ($n = 4$ cases of 40 drippers each, per group). Three-week-old lettuce seedlings (*Lactuca sativa*, cultivar “yellow leaves”) were grown for 80 days according to the water irrigation regimen depicted in Fig. 2a. As can be seen in Fig. 3a, there was a clear trend of reduction in root intrusion into the drippers with the increase in the copper oxide concentration in the dripper’s heads; from 54 % in the control to 43 % (24 % reduction, $p = 0.266$) and 31 % (43 % reduction, $p = 0.093$) in the drippers containing 12.5 and 25 % w/w copper oxide particles, respectively.

We tested again the efficacy of reducing the root penetration by the 25 % copper oxide-containing drippers as compared to the control drippers but enlarged the number of cases to 12 cases (480 drippers each) and used 3-week-old *Lactuca sativa*, *Noga* seedlings. Also in this experiment

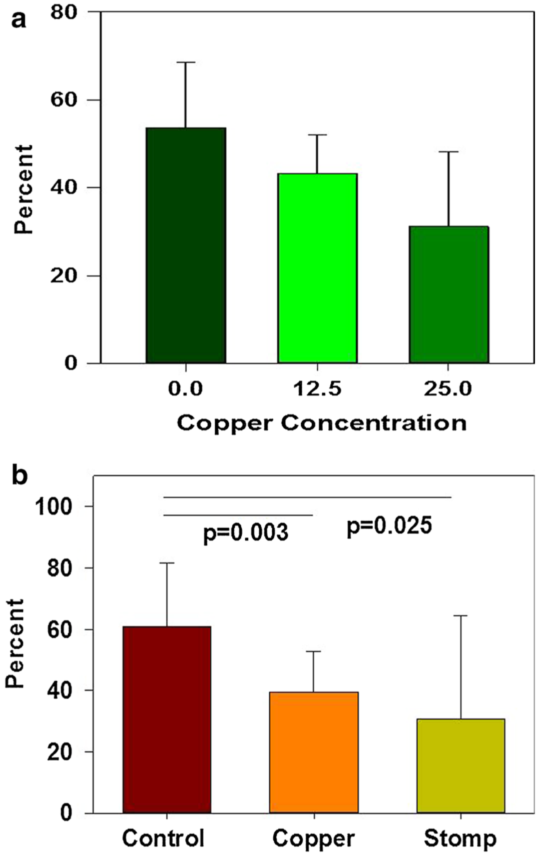

Fig. 3 **a** Mean and standard deviation of percent *Lactuca sativa* (cultivar "yellow leaves" seedlings) root intrusion into drippers with different copper oxide concentration ($n = 160$); **b** mean and standard deviation of percent *Lactuca sativa* (*Noga* seedlings) root intrusion for each type of dripper tested or Stomp® treatment ($n = 480$). The *p* values of a *t* test between the groups tested are shown

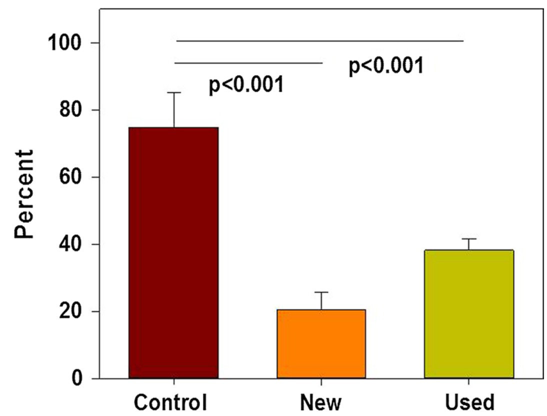

Fig. 4 Mean and standard deviation of percent *Lactuca sativa* ("yellow leaves" seedlings) root intrusion into new drippers or drippers through which 1000 l of water was passed before performing the experiment ($n = 160$). The *p* values of a *t* test between the groups tested are shown

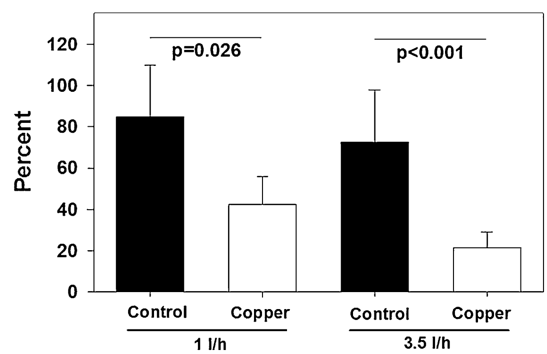

Fig. 5 Mean and standard deviation of percent tomato (*Lycopersicon esculentum*) root intrusion at 1 or 3.5 l/h water flow rate ($n = 120$). The *p* values of a *t* test between the groups tested are shown

after 60 days of growth using the water regimen depicted in Fig. 2b, there was a reduction in root intrusion into the drippers containing the copper oxide particles as compared to the control (35 % reduction, $p = 0.003$, Fig. 3b). In addition, we tested the root penetration in four cases that contained 160 drippers without copper but that were treated with a widely used herbicide (Stomp® 400 SC, BASF, Ireland) via the irrigation system as instructed by the manufacturer. The drippers that were treated with Stomp® showed a similar overall reduction in root penetration as that seen in the copper oxide-containing drippers, but the variability was significantly higher (Fig. 3b).

Experiment 2

In this experiment, we examined whether there is a reduction in the efficacy of preventing root intrusion into the drippers containing 25 % copper oxide particles after 1000 l of water has passed through each dripper ($n = 4$ cases of 40 drippers each, per group). We used *Lactuca sativa*, cultivar "yellow leaves" 3-week-old seedlings. As depicted in Fig. 4, the reduction in root penetration into the drippers containing copper oxide particles after 60 days of growth of growth using the water regimen depicted in Fig. 2c was even more drastic than in the first experiment using the same seedlings, from ~75 % in the control to ~21 % in the copper-containing drippers (~72 % reduction, $p < 0.001$). Importantly, even in drippers through which 1000 l of water was passed before performing the experiment, there were clear significant reductions (~45 % reduction, $p < 0.001$) in the root intrusion levels into the drippers as compared to the control.

Experiment 3

In this experiment, we examined the effect of the water flow rate on the capacity to reduce root intrusion by the copper

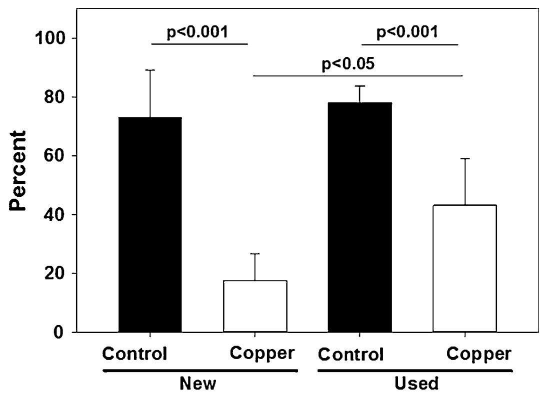

Fig. 6 Mean and standard deviation of percent tomato (*Lycopersicon esculentum*) root intrusion for new drippers or drippers in which 1720 l of sewage water was first passed through them ($n = 120$). The p values of a t test between the groups tested are shown

oxide impregnation. We used two types of UniRam™ AS drippers, with flow rates of 1 and 3.5 l/h. In each plot, 20 drippers were placed at a distance of 40 cm between each dripper. For each treatment, six plots were used with a total of 120 drippers per treatment. In each plot, two rows of 3-week-old tomato (*Lycopersicon esculentum*) seedlings were seeded with 40 cm distance between each seed in each row. The irrigation regime is described in Fig. 2c. As can be seen in Fig. 5, at a flow rate of 1 l/h, the presence of copper oxide particles in the drippers reduced the root intrusion into the drippers after 120 days by 50 % ($p = 0.026$), while at a flow rate of 3.5 l/h, the root intrusion reduction as compared to the control was reduced by 70 % ($p < 0.001$).

Experiment 4

In this last experiment, we examined whether the capacity of the drippers to inhibit root intrusion is affected when sewage water is used. We used UniRam™, either new or used drippers through which 1720 l of sewage water was first passed at a flow rates of 1 l/h, which customarily corresponds to 1.5–2 years of operation in the field. In each plot, 20 drippers were placed at a distance of 40 cm between each dripper. For each treatment, five plots were used with a total of 100 drippers per treatment. In each plot, two rows of 3-week-old tomato (*Lycopersicon esculentum*) seedlings were seeded with 40 cm distance between each seed in each row. The irrigation regime is detailed in Fig. 2d. As can be seen in Fig. 6, the presence of copper oxide particles in the new drippers reduced the root intrusion into the drippers by 76 %, from a mean of 73 to 17.5 % intrusion ($p < 0.001$), after 120 days of growth. Also the used drippers significantly reduced the root intrusion into the dripper, from a mean 78 to 43 % ($p < 0.001$), although as compared to the new drippers, there was reduced efficacy ($p = 0.013$).

Copper elution from drippers

The amount of copper in 250 ml of water before and after passing through a dripper containing copper oxide was less than 0.006 ppm (mg/l), which is the lower limit of detection of the assay. Copper oxide particles were present on the surface of the HDPE drippers containing 25 % copper oxide w/w, with no observable differences in the coverage in those not exposed or those exposed to 3350 l of water. The percentage of copper coverage on the surface of eight separate drippers though which 3350 l of water passed at a flow rate of 1 l/h during 140 days was 2 % lower in average than those found in eight separate drippers not exposed to water, as determined by SEM and X-ray photoelectron spectrum analysis (11.71 ± 0.53 vs 11.48 ± 1.59). 3350 l of water that passed through the drippers is equivalent to 3–4 years of irrigation using such flow rate irrigation system in a field.

Discussion and conclusions

A typical life span of SDI could be 15–20 years and depends of several factors, such as the type of water used, the bioflora that develops within the irrigation system, the maintenance treatment and the level of root intrusion into the emitters (Lamm et al. 2011). In this study, we analyzed the capacity of reducing root intrusion into the emitters by incorporating microscopic copper particles during the manufacture of the emitters, as copper is known as a potent algaecide (Borkow and Gabbay 2005; Murray-Gulde et al. 2002).

We used copper oxide for two main reasons: (a) copper oxide is a very reactive copper compound with potent biocidal properties, which is being used successfully in many consumer, industrial and medical device products (Borkow and Gabbay 2004, 2006; Borkow et al. 2007, 2010a, b; Borkow and Monk 2012; Borkow 2012), and (b) copper oxide is a non-soluble copper compound. Obviously in such products, it is important that the active ingredient in the product remains in the product for the life of the product; in this case that it would not be lost into the running water.

As was demonstrated in this study, impregnating the copper oxide particles into the drippers indeed very significantly reduced the root intrusion into the drippers, as demonstrated in all five experiments conducted. As expected, the reduction in the root intrusion was copper dose dependent. The inhibition of root intrusion occurred both in tomato and lettuce plants with different root system, supporting the notion that the effect is universal and not plant specific, although additional trials should test this hypothesis. The efficacy reached is similar to the current standard, i.e., treatment with Stomp®. Replacing Stomp® is advantageous as Stomp® treatment is environmentally unfriendly and time consuming, and in some countries its use is forbidden. Irrigation water can vary very much. Importantly, even when using sewage water, rich in organic material that can interact with the copper and quench the algaecidal efficacy, a very significant reduction in root intrusion was observed. The inhibition of root intrusion occurred both in dripper flow rate of 1 and 3.5 l/h. Both of these flow rates are very common in drip irrigation systems.

In conclusion, in this study we demonstrated that incorporation of copper oxide particles into the dripper's heads of SDI lines significantly and consistently reduced root penetration into the drippers. The efficacy is maintained even after very prolonged use allowing for reducing the frequency needed for replacing SDI systems.

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