

Dripper clogging: emphasis on the problem and how to minimize impact

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Abstract

Irrigation is a useful tool to achieve a better productivity and quality foods, which contributes to a higher efficient use of agriculture land. Drip irrigation is characterized by higher application efficiency, providing an efficient control of the irrigation depth required. Moreover, it has advantages such as lower evaporation loss and higher crop yields when associated with fertigation. However, dripper clogging is pointed out by several authors as the main limiting factor for a rapid adoption of drip irrigation on a larger scale. Emitter clogging susceptibility depends basically on five parameters: water quality, filtration system, fertilizer quality, labyrinth architectural layout and maintenance procedures. The adoption of chemical treatments helps to control biological agents and precipitates, making it possible to minimize the risk of clogging. This paper aims to understand how drip clogging process occurs, providing scientific arguments and support on the development of a standardized test pattern, making progress in order to identify commercial emitters that are less susceptible to clogging under field conditions.

Keywords

Drip irrigation; Water quality; Emitters.



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Introduction

Population growth requires a technical and competitive agriculture that provides food in greater quantity and better quality, which also demands a better use of cropland areas. Irrigation is one of the tools that can help achieve these objectives in modern agriculture (Angelakis et al., 2020; Kang et al., 2017).

At drip irrigation systems, soil moisture in the root zone is maintained at field capacity level with the application of small water volumes at higher frequency. This system works with reduced pressure (energy saving), with low evaporation losses and facilitating fertilizer application. It can reach higher irrigation efficiency (> 90%) and provide efficient irrigation management (Bernardo et al., 2006). However, emitter clogging is limiting a faster development of localized irrigation worldwide (Bounoua et al., 2016).

Impurities that cause emitter clogging are classified as chemical, physical and biological. The most common plugging causes observed at dripper labyrinths are: salt precipitation, microbiological growth, small insects, solid particles and plastic debris residues from irrigation system assembly (Pizarro Cabello, 1996). Usually clogging problems originate at water sources, such as wells and rivers, with high quantities of impurities (Capra & Scicolone, 1998).

One of the main factors in prolonging and maintaining the lifetime of drip irrigation equipment is water quality (Bucks et al., 1979; Capra & Scicolone, 1998). Low-flow emitters are more susceptible to variations in water quality, with the risk of emitter blockage, leading to failures in the uniformity of water distribution in the soil. In certain cases, higher flow emitters may also present clogging problems, usually related to low velocity throughout the emitter labyrinth, which can lead to particle deposition (Almeida et al., 2017; Coelho et al., 2022; Li et al., 2012).

This study aims to relate information on "clogging of drippers" with a focus on drip irrigation, in order to facilitate the understanding of possible causes and solutions, as well as to contribute to the advancement of studies in the area.

Water quality for irrigation

Most hydraulic systems experience performance changes during their lifetime. The water quality, the material and the operating factor of the system reduce the efficiency of the system and make the project more expensive with the increase costs of maintenance.

According to Lamm et al. (2006), the optimal condition for drip irrigation is the water to be treated to remove suspended particles, reducing pathogenic bacteria, odor, and turbidity.

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Local water treatment is performed at acceptable levels for the drip irrigation system.

Bucks et al. (1979) defined the factors affecting irrigation water quality, classifying potential risks according to concentration and type of problem (Table 1).

Table 1. Potential clogging risks of drip irrigation emitters.

Problem	Risk of clogging		
	Low	Moderate	High
Physical			
Suspended solids (ppm)	<50	50-100	>100
Chemical			
pH	<7	7-8	>8
Dissolved solids (ppm)	<500	500-2,000	>2,000
Mn (ppm)	<0.1	0.1-1.5	>1.5
Fe (ppm)	<0.1	0.1-1.5	>1.5
H ₂ S (ppm)	<0.5	0.1-2	>2
Biological			
Bacterial population (n° cm ⁻³)	<10,000	10,000-50,000	>50,000

Source: Bucks et al. (1979).

According to Lamm et al. (2006), in the field there are unfavorable circumstances for irrigation. Groundwater, rivers and lakes do not have a defined quality standard and sometimes can present very poor conditions for drip irrigation. Surface water sources may have different types of suspended and dissolved solids and biological organisms that varies along the year according to the watershed natural flow rates.

According to Pizarro Cabello (1996), there is no reliable method to evaluate the risk of clogging due to the use of certain types of irrigation water. One of the obstacle consists in the variation of some factors intervening, such as temperature and pH, which modifies the development of microorganisms and the formation of precipitates. In addition, there are other factors that are not related to water, for example, fertilizers.

Clogging factors-physical

Clogging by suspended solid particles has been reported as the most common type of clogging (Adin & Elimelech, 1989; Taylor et al., 1995). This type of problem is usually caused by the presence of suspended particles that can be of inorganic (sand, silt, clay and plastics) and organic origin (Bucks et al., 1979).

Clogging of a physical nature can occur in two ways. (1) by large particle diameter, which occurs when the particle size is larger than the emitter cross-section (usually sand particles) or (2) slow particle accumulation after filtration system, which occurs by the gradual deposition of fine particles of inorganic or organic matter in the pipe, usually located at the end of the dripline (Bounoua et al., 2016; Ravina et al., 1992; Taylor et al., 1995).

The main factors influencing clogging by suspended particles are particle diameter and particle concentration. It is difficult to determine which of the two factors makes the

greatest contribution to this phenomenon. Adin & Sacks (1991) argued that the severity of clogging, in many cases, depends more on the size than on the number of particles in the irrigation water. However, it is possible that an increase in the concentration of particles in irrigation water, even if they are of small diameters (< 0.01 mm), may have a significant effect on emitter's clogging (Niu et al., 2013).

The risk of clogging due to physical factors can be classified according to the concentration of suspended solid particles. For contents below 50 mg L⁻¹, the risk of clogging is low, while contents between 50 and 100 mg L⁻¹ present a moderate degree of risk, and contents above 100 mg L⁻¹ are classified as high risk of clogging (Bucks et al., 1979).

Clogging factors-chemical

According to Lili et al. (2016), clogging caused by chemical precipitation is more difficult to locate and treat at an advanced stage. Preventive treatments are recommended when the risks of clogging are higher. It can be caused by an excess of calcium and magnesium carbonate or sulfate, or by the oxidation of iron, which results in poorly soluble precipitates. These processes are promoted by certain conditions of temperature, humidity, pH, salt concentration and microorganisms (bacteria). It depends mainly on the composition and quality of the irrigation water, as well as the solubility of fertilizers used in fertigation.

According to Michalakos et al. (1997), surface water containing iron is usually identified as a precipitate (Fe₂O₃), while in the deeper layers of oxygen-depleted reservoirs it can be found in a dissolved ferrous state (FeO). In groundwater, iron is found in ferrous form and when pumped to the surface, it comes into contact with atmospheric oxygen, reacts, and produces a reddish-brown precipitate (Khozyem et al., 2019).

According to Pizarro Cabello (1996), the precipitated iron can be carried by the water, exiting through the emitter outlet, or blocked by bacterial filaments. Bacteria can adhere to the plastic or metal, preventing their dragging by the water. For example, non-filamentous bacteria, *Enterobacter* and *Pseudomonas* can also precipitate iron. These bacteria trap the precipitate in a gelatinous mass, generating a mucilage that clogs emitters or act as a cementing agent for small particles.

According to Ayers & Westcot (1985), 0.5 mg L⁻¹ should be the maximum allowable iron concentration. However, when filter values are included, in practice the maximum value is 2 mg L⁻¹. However, when sulfides or astringent substances are present in concentrations above 2 mg L⁻¹, the amount of dissolved iron must not exceed 0.5 mg L⁻¹.

To be used without restrictions for irrigation, Bucks et al. (1979) established that water should have an iron concentration lower than 0.1 mg L⁻¹. In drip irrigation systems, the use of water with iron contents higher than 1.5 mg L⁻¹ has serious limitations due to the high risk of dripper clogging.

Clogging factors-biological

According to Sánchez & Viafara (1970), biological clogging is caused by the accumulation of micro and macro-organisms. In practice, all water contains small amounts of fungi, bacteria, and algae (Stewart-Wade, 2011). When these waters are stored in the open air and sunlight, taking advantage of the dissolved nutrients, these organisms proliferate very quickly, producing a gelatinous organic mass that clogs the irrigation system and filters.

One of the possible causes of the development of clogging are the microorganisms inside the irrigation systems, which can be present in any position of the network, although their greatest damage is on emitters (Pizarro Cabello, 1996).

The presence of algae, especially in the filters, obstructs the passage of water and causes various types of problems, making frequent backwashing necessary. These microorganisms do not proliferate inside the tubes, although the residues of dead algae that pass through the filters feed the bacteria, which are apt to grow in the absence of light (Resende et al., 2000).

According to Liu et al. (2015), biocorrosion caused by iron-oxidizing bacteria is due to a heterogeneous group of microorganisms (bacteria of the genus *Gallionella*, *Sphaerotillus*, and *Crenothrix* among the most frequent) that have in common the ability to oxidize the ferric ion (Fe³⁺) and ferrous (Fe²⁺) serving as a primary source of energy for these bacteria. This oxidation results in the formation of insoluble ferric hydroxide (Fe (OH)₃). The bacteria form a red, yellow, or tan colored slime, forming ochre (colored aggregates). For example, the ferro bacterium *Gallionella* forms iron stalks or strips, which are deposited around the body by secretions. This deposit can trap rapidly suspended particles that result in exponential growth of the colony (Lamm et al., 2006).

Temperature, pH and the presence of organic carbon in the water are elements that influence the growth of bacteria that cause clogging. Although most bacteria require an optimum pH level, many grow at a pH level of between 3.5 and 8.5. Therefore, the problem is not solved by simply changing the pH of the water. On the other hand, the optimum temperature

ranges from 20 to 30°C, but bacteria continue to grow less rapidly at temperatures outside this range (Pizarro Cabello, 1996).

Preventive actions

The filtration system, designed to retain the organic or inorganic particles, is necessary for a drip irrigation system (Bucks et al., 1979; Ravina et al., 1992). There are two main filtration mechanisms; (1) mesh filters (screen and discs) and (2) granular filters (sand filters) (Adin & Elimelech, 1989). The sizing of the filtration system is mainly determined by the quality of the water to be used in the system (Bucks et al., 1979).

Nevertheless, very small particles such as clay, silt, microscopic organisms, algae and some bacteria are not retained by traditional irrigation filtration system and can cause clogging by the formation of larger particles due to the accumulation and/or aggregation of particles (Bounoua et al., 2016; Niu et al., 2013).

For fine particles, another strategy adopted as a prevention of emitter clogging is flushing of driplines. This procedure consists of opening the end of the lateral lines allowing the removal of particles by water flow (Puig-Bargues et al., 2010), reducing the risk of clogging.

The main parameter to avoid clogging by chemical agents is the control of the pH of the irrigation water. The presence of some ions, mainly carbonates, phosphates, hydroxides and sulfates, at a pH higher than 7, promotes the formation of precipitates, which tend to accumulate in the lateral line, causing clogging (Lamm et al., 2006).

To control pH, treatment of irrigation water with acid is recommended (Nakayama & Bucks, 1991; Zhang et al., 2017). Nakayama & Bucks (1991) recommend avoiding certain fertilizers or chemical additives that increase pH to the point of precipitating carbonates, phosphates, and hydroxides.

The use of chlorination is the main technique used to control microorganisms and their secretions in drip irrigation (Adin & Elimelech, 1989; Tajrishy et al., 1994). Chlorination cannot completely prevent the risk of clogging an emitter. However, this technique is the basis of treatment against biological clogging (Zhou et al., 2017).

During the chlorination process, the concentration of free chlorine present in the water represents the effectiveness of the procedure since it is responsible for contacting the microorganisms. Different concentrations of free chlorine and the time required for effective treatment are recommended (Table 2).

Table 2. Use of chlorination for biological control in drippers.

Reference studies	Concentration (mg L ⁻¹)	Time
Ravina et al. (1992)	3 - 5	3 hours
Tajrishy et al. (1994)	0 - 4	Continuous
Tajrishy et al. (1994)	2 - 6	In the last hour of irrigation
Song et al. (2017)	2.5 - 10	0.5 - 2 hours

Source: Authors, 2022.

Perspectives

Due to the simultaneous action of several factors, drip clogging must continue to be a problem for a long time. One approach is to individualize the action of physical, chemical and biological agents. However, there is currently no standardized test for assessing the sensitivity of emitters. In general, clogging by solid particles is more prevalent. Several test methodologies have been adopted for clogging tests, varying concentrations and diameters of solid particles, test levels and number of repetitions (Niu et al., 2013; Qingsong et al., 2008). Therefore, standardizing the procedure would facilitate the analysis of the susceptibility to clogging of a given emitter.

Another approach always cited in the literature as a future suggestion for the irrigation industry it is the development of new emitters capable of minimizing the effects of clogging. Commonly, emitters have labyrinth-like channels, which are responsible for dissipating energy, resulting in good uniformity of emitter distribution (Qingsong et al., 2008; Song et al., 2017). However, because they present small flow sections, particle deposition occurs inside the channel, causing emitter clogging (Ravina et al., 1992).

To evaluate the anti-clogging capability of emitters, a few studies have been conducted to determine the best architectural design. Zhang et al. (2017) created a method to evaluate the performance of a trapezoidal emitter by varying the channel dimensions (width and height of teeth, diameter, depth), while Wei et al. (2012) evaluated 16 combinations of rectangular and zigzag labyrinths by varying the width, length, height and number of teeth.

Zhou et al. (2017) created an anti-clogging index, which has the main influence on the length of the labyrinth, the ratio of channel width to depth, and the average shear force of water on the pipe wall.

The ratio of channel pitch diameter to tooth height is insignificant for good emitter performance. However, the angle between the teeth, and the ratios of pitch diameter to channel width, tooth width to tooth depth, and tooth height to channel pitch diameter, are significant in that order (Zhang et al., 2010).

Using Computational Fluid Dynamic (CFD) simulation software, it is possible to predict the hydraulic performance of an emitter, which is capable of demonstrating the variation in pressure, flow velocity and other flow characteristics,

indicating where areas of suspended particle deposition might occur (Wei et al., 2008; Zhang et al., 2011), possibly allowing the development of new emitters that are less susceptible to clogging.

Another future perspective that may help minimize the problem of dripper clogging in drip irrigation is the use of plastic nanomaterials that prevent the growth of biofilms and precipitates on plastic surfaces. Franci et al. (2015) and Miao et al. (2019), report the effects of nanoplastics on biofilms as a function of particle size, concentration and surface type, demonstrating that these materials are potential antibacterial agents.

Conclusions

The susceptibility of an emitter to clogging depends basically on five parameters: water quality, filtration system, fertilizer quality, labyrinth architectural layout and maintenance procedures. By carrying out appropriate treatments to control the action of physical, chemical and biological agents associated with an anti-clogging emitter architecture, it is possible to minimize the risk of clogging.

Investigation of individual clogging processes can provide scientific arguments and assist in the development of a standardized test, facilitating the development of emitters less susceptible to clogging.

The development of plastic additives based on nanomaterials to be incorporated into the dripper injection process has the potential to minimize the incrustation of chemical precipitates and microbial biofilms on the surface of the emitters' plastic labyrinths. Although this technology is not yet being adopted by the localized irrigation equipment industry, it should be a future technological ally to be considered, as the architecture variation of the different emitters commercialized in the last decades, the adopting of filter systems and the recommended maintenance processes, helped to minimize the effects, but did not definitively solve the problem of clogging of emitters in the field.

References

- Adin, A., & Elimelech, M. (1989). Particle filtration for wastewater irrigation. *Journal of irrigation and drainage engineering*, 115(3), 474-487. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1989\)115:3\(474\)](https://doi.org/10.1061/(ASCE)0733-9437(1989)115:3(474))
- Adin, A., & Sacks, M. (1991). Dripper-clogging factors in wastewater irrigation. *Journal of Irrigation and Drainage Engineering*, 117(6), 813-826. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1991\)117:6\(813\)](https://doi.org/10.1061/(ASCE)0733-9437(1991)117:6(813))
- Almeida, A. N. D., Coelho, R. D., Costa, J. D. O., & Farias, A. J. (2017). Methodology for dimensioning of a center pivot irrigation system operating with dripper type emitter. *Engenharia Agrícola*, 37, 828-837. http://dx.doi.org/10.1590/1809-4430-Eng_Agric.v37n4p828-837/2017
- Angelakis, A. N., Zaccaria, D., Krasilnikoff, J., Salgot, M., Bazza, M., Roccaro, P., ... & Fereres, E. (2020). Irrigation of world agricultural lands: Evolution through the Millennia. *Water*, 12(5), 1285. <https://doi.org/10.3390/w12051285>
- Ayers, R. S., & Westcot, D. W. (1985). *Water quality for agriculture*. Rome: Food and Agriculture Organization of the United Nations.
- Bernardo, S., Soares, A. A., Mantovani, E. C. (2006). *Manual de irrigação*. 8.ed. Viçosa: Ed. UFV. 625p.
- Bounoua, S., Tomas, S., Labille, J., Molle, B., Granier, J., Haldenwang, P., & Izzati, S. N. (2016). Understanding physical clogging in drip irrigation: in situ, in-lab and numerical approaches. *Irrigation Science*, 34(4), 327-342. <https://doi.org/10.1007/s00271-016-0506-8>

- Bucks, D. A., Nakayama, F. S., & Gilbert, R. G. (1979). Trickle irrigation water quality and preventive maintenance. *Agricultural Water Management*, 2(2), 149-162. [https://doi.org/10.1016/0378-3774\(79\)90028-3](https://doi.org/10.1016/0378-3774(79)90028-3)
- Capra, A., & Scicolone, B. (1998). Water quality and distribution uniformity in drip/trickle irrigation systems. *Journal of Agricultural Engineering Research*, 70(4), 355-365. <https://doi.org/10.1006/jaer.1998.0287>
- Coelho, R. D., de Almeida, A. N., de Oliveira Costa, J., & de Sousa Pereira, D. J. (2022). Mobile drip irrigation (MDI): Clogging of high flow emitters caused by dragging of driplines on the ground and by solid particles in the irrigation water. *Agricultural Water Management*, 263, 107454. <https://doi.org/10.1016/j.agwat.2022.107454>
- Franci, G., Falanga, A., Galdiero, S., Palomba, L., Rai, M., Morelli, G., & Galdiero, M. (2015). Silver nanoparticles as potential antibacterial agents. *Molecules*, 20(5), 8856-8874. <https://doi.org/10.3390/molecules20058856>
- Kang, S., Hao, X., Du, T., Tong, L., Su, X., Lu, H., ... & Ding, R. (2017). Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. *Agricultural Water Management*, 179, 5-17. <https://doi.org/10.1016/j.agwat.2016.05.007>
- Khozyem, H., Hamdan, A., Tantawy, A. A., Emam, A., & Elbadry, E. (2019). Distribution and origin of iron and manganese in groundwater: case study, Balat-Teneida area, El-Dakhla Basin, Egypt. *Arabian Journal of Geosciences*, 12(16), 1-16. <https://doi.org/10.1007/s12517-019-4689-1>
- Lamm, F. R., Ayars, J. E., & Nakayama, F. S. (2006). *Microirrigation for crop production: design, operation, and management*. Elsevier.
- Li, G. B., Li, Y. K., Xu, T. W., Liu, Y. Z., Jin, H., Yang, P. L., ... & Tian, Z. F. (2012). Effects of average velocity on the growth and surface topography of biofilms attached to the reclaimed wastewater drip irrigation system laterals. *Irrigation Science*, 30(2), 103-113. <https://doi.org/10.1007/s00271-011-0266-4>
- Lili, Z., Yang, P., Ren, S., Li, Y., Liu, Y., & Xia, Y. (2016). Chemical clogging of emitters and evaluation of their suitability for saline water drip irrigation. *Irrigation and Drainage*, 65(4), 439-450. <https://doi.org/10.1002/ird.1972>
- Liu, H., Fu, C., Gu, T., Zhang, G., Lv, Y., Wang, H., & Liu, H. (2015). Corrosion behavior of carbon steel in the presence of sulfate reducing bacteria and iron oxidizing bacteria cultured in oilfield produced water. *Corrosion Science*, 100, 484-495. <https://doi.org/https://doi.org/10.1016/j.corsci.2015.08.023>
- Miao, L., Hou, J., You, G., Liu, Z., Liu, S., Li, T., ... & Qu, H. (2019). Acute effects of nanoplastics and microplastics on periphytic biofilms depending on particle size, concentration and surface modification. *Environmental Pollution*, 255, 113300. <https://doi.org/10.1016/j.envpol.2019.113300>
- Michalakos, G. D., Nieva, J. M., Vayenas, D. V., & Lyberatos, G. (1997). Removal of iron from potable water using a trickling filter. *Water research*, 31(5), 991-996. [https://doi.org/10.1016/S0043-1354\(96\)00343-0](https://doi.org/10.1016/S0043-1354(96)00343-0)
- Nakayama, F. S., & Bucks, D. A. (1991). Water quality in drip/trickle irrigation: a review. *Irrigation science*, 12(4), 187-192. <https://doi.org/10.1007/BF00190522>
- Niu, W., Liu, L., & Chen, X. (2013). Influence of fine particle size and concentration on the clogging of labyrinth emitters. *Irrigation Science*, 31(4), 545-555. <https://doi.org/10.1007/s00271-012-0328-2>
- Pizarro Cabello, F. (1996). *Riegos localizados de alta frecuencia*. 2ª ed. Mundi-Prensa, Madrid.
- Puig-Bargues, J., Arbat, G., Elbana, M., Duran-Ros, M., Barragán, J., De Cartagena, F. R., & Lamm, F. R. (2010). Effect of flushing frequency on emitter clogging in microirrigation with effluents. *Agricultural Water Management*, 97(6), 883-891. <https://doi.org/10.1016/j.agwat.2010.01.019>
- Qingsong, W., Gang, L., Jie, L., Yusheng, S., Wenchu, D., & Shuhuai, H. (2008). Evaluations of emitter clogging in drip irrigation by two-phase flow simulations and laboratory experiments. *Computers and Electronics in Agriculture*, 63(2), 294-303. <https://doi.org/10.1016/j.compag.2008.03.008>
- Ravina, I., Paz, E., Sofer, Z., Marcu, A., Shisha, A., & Sagi, G. (1992). Control of emitter clogging in drip irrigation with reclaimed wastewater. *Irrigation Science*, 13(3), 129-139. <https://doi.org/10.1007/BF00191055>
- Resende, R. S., Coelho, R. D., & Piedade, S. M. D. S. (2000). Suscetibilidade de gotejadores ao entupimento de causa biológica. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 4, 368-375. <https://doi.org/10.1590/S1415-4366200000300011>
- Sánchez, L. D., & Viáfara, C. A. (2014). Impacto de los sólidos suspendidos totales sobre la obstrucción en emisores de riego localizado de alta frecuencia. *Ingeniería y Competitividad*, 16(2), 199-210. <https://doi.org/10.25100/iyv.v16i2.3695>
- Song, P., Li, Y., Zhou, B., Zhou, C., Zhang, Z., & Li, J. (2017). Controlling mechanism of chlorination on emitter bio-clogging for drip irrigation using reclaimed water. *Agricultural Water Management*, 184, 36-45. <https://doi.org/10.1016/j.agwat.2016.12.017>
- Stewart-Wade, S. M. (2011). Plant pathogens in recycled irrigation water in commercial plant nurseries and greenhouses: their detection and management. *Irrigation Science*, 29(4), 267-297. <https://doi.org/10.1007/s00271-011-0285-1>
- Tajrishy, M. A., Hills, D. J., & Tchobanoglous, G. (1994). Pretreatment of secondary effluent for drip irrigation. *Journal of Irrigation and Drainage Engineering*, 120(4), 716-731. [https://doi.org/10.1061/\(ASCE\)0733-9437\(1994\)120:4\(716\)](https://doi.org/10.1061/(ASCE)0733-9437(1994)120:4(716))
- Taylor, H. D., Bastos, R. K. X., Pearson, H. W., & Mara, D. D. (1995). Drip irrigation with waste stabilisation pond effluents: Solving the problem of emitter fouling. *Water Science and Technology*, 31(12), 417-424. [https://doi.org/10.1016/0273-1223\(95\)00528-U](https://doi.org/10.1016/0273-1223(95)00528-U)
- Wei, Q., Shi, Y., Lu, G., Dong, W., & Huang, S. (2008). Rapid evaluations of anticlogging performance of drip emitters by laboratorial short-cycle tests. *Journal of irrigation and drainage engineering*, 134(3), 298-304. <https://doi.org/10.1061/0733-9437>
- Wei, Z., Cao, M., Liu, X., Tang, Y., & Lu, B. (2012). Flow behaviour analysis and experimental investigation for emitter micro-channels. *Chinese journal of mechanical engineering*, 25(4), 729-737. <https://doi.org/10.3901/CJME>
- Zhang, J., Zhao, W., & Lu, B. (2011). New method of hydraulic performance evaluation on emitters with labyrinth channels. *Journal of irrigation and drainage engineering*, 137(12), 811-815. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000365](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000365)
- Zhang, J., Zhao, W., Tang, Y., & Lu, B. (2010). Anti-clogging performance evaluation and parameterized design of emitters with labyrinth channels. *Computers and Electronics in Agriculture*, 74(1), 59-65. <https://doi.org/10.1016/j.compag.2010.06.005>
- Zhang, L., Wu, P., Zhu, D., & Zheng, C. (2017). Effect of pulsating pressure on labyrinth emitter clogging. *Irrigation Science*, 35(4), 267-274. <https://doi.org/10.1007/s00271-017-0532-1>
- Zhou, B., Li, Y., Song, P., Zhou, Y., Yu, Y., & Bralts, V. (2017). Anti-clogging evaluation for drip irrigation emitters using reclaimed water. *Irrigation Science*, 35(3). <https://doi.org/10.1007/s00271-016-0530-8>