# Evaluation of Pre-packaged Agricultural Drip Irrigation Kits



By

Shen Huang

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Engineering as
Recommended by the Department of
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## ABSTRACT

The purpose of this thesis is to conduct user testing and performance evaluation of two different agricultural pre-packaged drip irrigation kit (PDIK) systems: Chapin Bucket Kit and International Design Enterprises (IDE) drip kit. PDIK systems are a cost-effective type of appropriate technology for the developing world because they reduce agricultural water consumption and can increase crop yield over other methods of irrigation. Overall user testing indicates preference for the IDE drip kit because of ease of installation, low cost, and suitable size for the average household plot. On the other hand, the Chapin Bucket Kit performs better in laboratory evaluation in terms of emitter performance, materials strength, and filter clogging . Ultimately, it is up to users to decide what are the trade-offs that can be made when choosing a PDIK system.

This study is conducted under the MIT Development Lab Technology Evaluation and Verification Program (D-lab TEV) and has been financially supported by the MIT Public Service Center and the MIT Department of Foreign Languages and Literature.

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# 1 Introduction

The purpose of this thesis is to conduct qualitative user testing and quantitative performance evaluation of two different pre-packaged drip irrigation kit (PDIK) systems from two different manufacturers, Chapin Living Waters and International Development Enterprises. PDIK systems are a cost-effective type of appropriate technology for the developing world.They not only reduce agricultural water consumption but also can increase yield over other methods of irrigation. This study is part of the MIT Development Lab Technology Evaluation and Verification Program (D-Lab TEV), which seeks to become the authority on product testing, evaluation, and benchmarking for the developing world and generate a comprehensive bank of peer-reviewed literature on appropriate technologies. This study has been financially supported by the MIT Public Service Center and the MIT Department of Foreign Languages and Literature.

Section 2 explains the motivation of this thesis project. Section 3 gives a comparative overview of drip irrigation in comparison to other irrigation methods, including typical components of a PDIK system and a cost-benefit analysis. Section 4 gives a survey of existing PDIK systems in the developing world. Section 5 describes the user testing of selected PDIK systems conducted with community partner Grupo Fenix in Sabana Grande, Nicaragua. Section 6 describes the laboratory testing and evaluation of PDIK systems, namely for emitter discharge performance, material strengths and human factors, and filter clogging.

# 2 Motivation

## 2.1 Appropriate technology problems

In the on-going struggle to increase quality of life and promote economic growth for people in the developing world, there exists a large market of *appropriate technologies.* Appropriate technologies are founded on the "small is beautiful" principle pioneered by economist E.F.

Schumacher in the 1970s. In other words, these technologies are broadly contextualized to be small-scale, affordable, simple, locally produced, locally maintained, energy efficient, and environmentally friendly. However, the majority of appropriate technologies on the market have not been tested or evaluated.[1] As a result, frequently appropriate technologies lack information about their reliability and can even pose economic risks to the users [3]. As a result, international development practitioners may disseminate appropriate technologies for use in developing countries with good intentions, but they also may create unintentional problems if products have unreliable functionality, are too complex, break, or cannot be locally repaired.

To address this need for more information, the Massachusetts Institute of Technology Development Lab (D-Lab) has recently created the Technology Evaluation and Verification Program (TEV) to become the authority on testing, evaluation, and benchmarking of technologies designed across sectors for the developing world. D-Lab is a program at MIT that focuses on improving the quality of life of low-income households through the creation and implementation of low cost technologies. TEV aims to produce peer-reviewed literature on appropriate technologies that have both undergone laboratory performance testing and user testing in the field with community partners, in order to understand how the product performs in different contexts. Currently, the TEV program is focusing on examining technology within three suites, agriculture, energy, and water. Many products that fall into these suites focus on many development issues that have been articulated by the United Nations Millennium Development Goals (UN MDG) [4].

## 2.2 Water use concerns

Because subsistence farming is the bedrock of most people's lives in the developing world, improved agriculture methods can help directly address two UN MDG:

*Goal 1*: Eradicate extreme poverty and hunger.

[1]Personal communication with Mr. Derek Brine and Ms. Rebecca Smith, October 2011

*Target 1.A*: Halve, between 1990 and 2015, the proportion of people whose income is less than $1 a day. [4]

*Goal 7*: Ensure environmental sustainability.
*Target 7.A*: Integrate the principles of sustainable development into country policies and programmes; reverse loss of environmental resources.
*Indicator 7.5*: Proportion of total water resources used. [5]

In addition, the United Nations has defined the right to water for personal and domestic use as a fundamental human right that is "indispensable to leading a life full of dignity" because water is a limited resource that is necessary for human survival [6]. However, due to the fact that global demand for water continues to grow due to population increase, lifestyle changes, and industrialization, in the developing world water continues to become more and more scarce. Water must be managed and used in a more efficient, conservative manner. Of all the factors that contribute to the consumption of water, agriculture comprise 70% of total use, with 90% is attributed to irrigation [7]. Governments, companies, non-profit organizations, international aid groups, individuals, and small farming businesses continuously investigate, implement, and disseminate better designs of irrigation systems that provide more efficient use of water in a cost effective manner. In the past twenty years, pre-packaged drip irrigation kits have raised attention because of their affordability and high rate of return on investment. Both large aid organizations (e.g. the World Bank) and drip irrigation manufacturers are eager to disseminate such kits on a large scale. They have set the goal of bringing 1 million hectares per year under low cost irrigation in the next 15 years, yet little has been done to conduct feasibility tests or evaluation of the actual technologies that will be used to accomplish this objective [8, p.4].

Under the MIT D-lab TEV program, irrigation from the point of view of low-income subsistence farmer is examined in the context of northern rural Nicaragua, where our community partner is based. In particular, this thesis will investigate the testing and performance evaluation of two different pre-packaged drip irrigation kit systems that have contrasting marketing approaches (for-profit or non-profit).

# 3 Background

## 3.1 Comparison of irrigation methods

The three methods of irrigation–sprinkler, surface, drip–all pose both advantages and disadvantages for the user. Therefore, it is up to the user to decide which method is most appropriate in the context of personal economic means, the local environmental conditions, assembly labor and maintenance requirements, previous experience with irrigation, and types of crops grown [1]. A graphic representation of the three methods is depicted in Figure 3.1.

**(a)** Sprinkler irrigation [9] **(b)** Surface irrigation [10] **(c)** Drip irrigation [11]

**Figure 3.1:** Irrigation methods. Adapted from NRCS (2002) and Arizona Drip Systems (2011).

As shown in Figure 3.1a, *sprinkler irrigation* distributes piped water by overhead high-pressure sprinklers. Water is sprayed to cover as much surface area as possible. As shown in Figure 3.1b, another method is *surface irrigation*, which distributes water directly over the soil surface by gravity. Water is typically applied in either constructed channels or floods to infiltrate the soil. And finally, as shown in Figure 3.1c, *drip irrigation* distributes piped water through emitters in series of dripping motions. Water is delivered directly to only the roots of the plants.

### 3.1.1 Price

According to Polak, the most important consideration and constraint for low-income people in choosing among similar products is price [12, p.65]. The World Bank estimates that as of 2008, the typical income is less than $1.25 per day for 1,345 million people[13]. To put it in perspective, it takes two entire days for a person in Bangladesh or Zimbabwe to earn one dollar, in contrast to the ten minutes of an unskilled worker in the United States [12, p.66]. Out of the three irrigation systems, drip irrigation is the least expensive option, ranging from $5 up to $120 and gives the user further savings because the total amount of water needed to run the system is minimal. On the other hand, surface irrigation does not require any capital investments on purchasing the system, but the costs of water and labor required to maintain the irrigation method can become costly and time-consuming to a low-income farmer. Lastly, sprinkler irrigation systems typically are prohibitively expensive and are complicated to assemble, ranging from $700-$3500 [14].

### 3.1.2 Environmental factors

Besides financial costs, environmental factors are also crucial to selecting the type of system to use due to the fact that irrigation systems are implemented outdoors and are exposed to the elements for long periods of time. Figure 3.2 summarizes various environmental factors to take into consideration.

### 3.1.3 Technical considerations

Other considerations that factor in deciding among irrigation systems are technical: how does the system suit the types of crops intended to be grown, what is the fundamental function of the method, how technically complex is the irrigation system, and what is the community's knowledge of existing systems [1]. Irrigation systems must serve the purpose of nourishing crops. Surface irrigation can be used for all crops because it consists of simply applying water over a field in channels or floods, but sprinkler and drip irrigation are mainly

| Condition | Subcondition | Sprinkler | Surface | Drip |
|---|---|---|---|---|
| Soil type | Sandy | + | - | + |
| | Loam or clay | + | ++ | + |
| | Variety of soil types | + | - | + |
| Slope | Very steep with no rice terracing | + | - | + |
| | Very steep with rice terracing | - | + | - |
| Climate | Very windy | - | + | + |
| Water availability | Efficient use of water | + | - | ++ |
| Water quality | Water has sediment | - | + | - |
| | Water has dissolved salts | + | - | ++ |

**Figure 3.2:** Environmental considerations in selecting types of irrigation systems. Adapted from FAO [1].

used for vegetables and fruit trees (high value crops) due to the fact that they are high value capital equipment and more technologically complex. In addition, another consideration is the spacing between crops. Drip irrigation cannot work effectively for closely-spaced crops because it consists of drip tape whose pre-manufactured perforations are typically spaced more than a few inches apart.

The fundamental function of the system often is tied closed to the water consumption it requires. Drip irrigation systems directly deliver water constantly throughout the day to the roots of plants (see 3.3, can help conserve precious water resources, and facilitate and prolong the growth rate of crops. This targeted zone of water delivery helps reduce the growth of undesired plants. Surface and sprinkler irrigation methods are applied to cover as much surface area as possible.

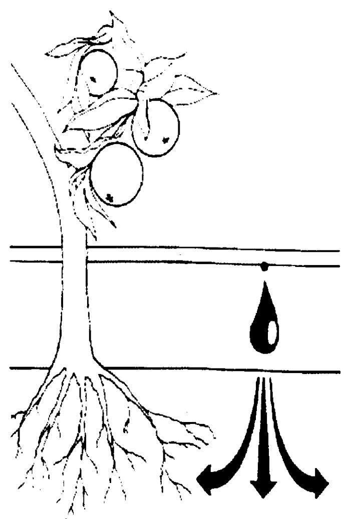


**Figure 3.3:** Water delivery method to plant root zone from drip irrigation. Adapted from FAO [1].

The technical considerations are important because the more complex the system is, the more maintenance is required. If the community is not already familiar with the system, a newly introduced system may lead to unintended consequences. For example, spare parts may not be readily available to purchase, community members may not know how to repair the system, or even the community members will not necessarily accept the newly introduced system or feel a sense of ownership that is required for successful implementation and upkeep. These disadvantages should be determined in the cost-benefit analysis stage, rather than discovered after investing in the product.

In examining the context of our community partner, we find that drip irrigation is overall more advantageous here than are the other systems. Nicaragua is the second poorest country in the western hemisphere, so the costs of any agricultural tool is the foremost consideration. Northern Nicaragua is a mountainous region that suffers from water shortage because one half of the year undergoes the dry season. The staple crop is corn, and small vegetable gardens and fruit trees are common in households. People typically eke out a living due to their low income and traditional lack of planting during the dry season. Drip irrigation systems are relatively affordable and can potentially provide farmers the necessary tools to grow more food even with a conserved amount of water.

Originally developed in the 1960s for large commercial farms, drip irrigation systems in recent years have become scaled down and simplified for household farms in the form of pre-packaged drip irrigation kits. For this investigation, pre-packaged drip irrigation kits (referred to as PDIK from now on) will be examined, because they are typically marketed to farmers in the developing world. PDIK consist of prepackaged components in a bundle kit so that household farmers can conveniently assemble a complete system that has already been sized appropriately for their garden plot.

## 3.2 Typical components

In contrast to the more open-ended flexibility of regular drip irrigation systems, PDIK systems simplify the installation process by including all the essential components and already have two key design choices already decided by the manufacturers: water source and size. PDIK systems use the pressure head created by elevating a water source to propel the water by the force of gravity through a system of polyethylene drip tape laterals that release small quantities of water at pre-determined intervals corresponding to plant location. Manufacturers determine the size of PDIK systems, which range from 40-100 $m^2$, which is the typical available land area of a household farmer. The general design schematic of a typical PDIK system is represented in Figure 3.4.

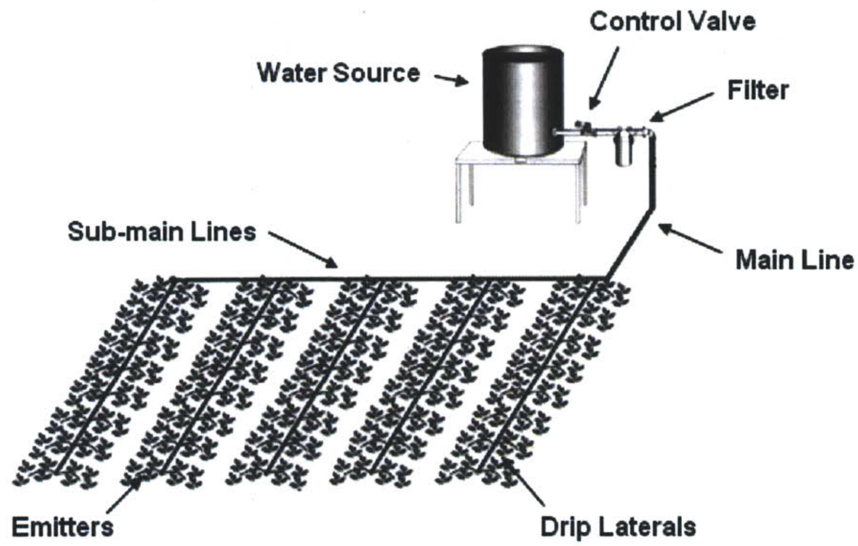



**Figure 3.4:** Components of a typical pre-packaged drip irrigation system. Adapted from RCSD (2008) [2]

### Water Source

PDIK systems use elevated water sources in the form of a water bag or a container like a bucket to store and provide the necessary pressure head to drive the water flow through the main lines to the ends of the drip laterals. By solely elevating the water source at sufficient enough height, PDIK systems reduce costs from the need to have equipment and power to pump water to drive the flow. The disadvantage is that farmers will have to haul water and fill the water source manually.

### Control Valve

PDIK systems may include a control valve that regulates the flow of the water from the source to the rest of the system.

### Filter

In order to be functional, PDIK systems all have water filters in the water source to prevent clogging of drip tape and emitters by inorganic (silt, sand, clay, and chemical precipitates) or organic (algae and bacteria) materials. The water filters are typically simple screens. For long-term use of PDIK systems, frequency of replacement and size of particles passing through the filters need to be considered. Furthermore, water sources like water bags and buckets are exposed, so entry of foreign particles like sand or leaves can be prevented by tying a piece of cloth over the opening.

### Main and Submain Lines

Main and submain lines transport the water from the the source to the drip lateral lines. Typically these lines are made from polyethylene.

### Drip Laterals

Drip laterals are smaller in diameter than main or submains to increase the pressure so that the water can drip out of the pre-perforated holes. Due to friction loss along the drip laterals, flow rates will accordingly drop and as a result, there is a higher possibility clogging in the emitters. Drip laterals are also typically made from polyethylene in PDIK and can age overtime due to UV damage.

### Emitters

Emitters control the rate of water dripping out into the soil. They can be pre-built into the drip laterals or can consist of straws protruding from the holes in the drip laterals. The spacing between emitters vary depending on the manufacturer, but usually are determined to fit typical spacing needs for vegetable plants.

### Instruction Manual

In order to be user-friendly, PDIK systems usually include an instruction manual on the installation and maintenance process.

## 3.3 Cost-benefit analysis

Even when users have chosen drip irrigation over methods of irrigation, they still should understand the strengths and weaknesses of the system. In particular, the design decisions of PDIK systems come from manufacturers and not necessarily the users, so it is important that people understand how to use and modify PDIK systems to suit their needs.

The strengths of PDIK systems are that they provide more efficient application of water, promote more targeted application of fertilizer, increase crop yield, and are scalable. By constantly dripping water onto only the roots of plants at a close range, soil moisture levels are optimized and the growth of unwanted weeds are minimized. As a result, farmers can enjoy increased crop growth and also plant more times in the year. As multinational drip irrigation company Jain Irrigation Inc. puts it, drip irrigation gives "More crop per drop." Farmers can also conserve the use of fertilizer by only applying it in a localized fashion. PDIK systems reduce water consumption by delivering only as much water is in the water source (typically between 5-30 gallons) to the entire plot of land. In addition, they prevent further water loss due to evaporation because the flow of water is regulated in a series of dripping motions, as opposed to spraying or flooding as the other irrigation methods. In addition, PDIK systems are meant to be affordable and scalable. Stand-alone PDIK systems only include the minimal number of parts to create a functional, user-friendly system so that people can afford to invest in such a technology with no prior experience in drip irrigation. Farmers can buy a basic kit to start small and once they have generated more income from using this system, they can re-invest a portion of their extra funds into buying expansion packs.

The weaknesses of PDIK systems mainly stem from extensive maintenance issues. First of all, users must be aware of the performance requirements and know how to service the system. Filters must be clean to prevent clogging of emitters. Damage to the polyethylene materials must be regularly inspected, so that water is not wasted by flowing through unplanned punctures. Farmers must have the materials to repair any punctures, such as

PVC glue, and these materials may not necessarily always be locally available. There must be enough pressure head for the system to be functional and because of the low pressure of PDIK, factors like unleveled land or clogged emitters can prevent uniform distribution of water flow. The main lines, sub-main lines, and drip laterals must lie flat and undisturbed at all times, even if farmers are plowing or harvesting the crops. Above all, if the system fails and remains inactive for long periods of time, there may not be sufficient enough water to maintain plant growth because the area of the roots that are watered is shallow.

# 4 Literature review

## 4.1 Chaplin Living Waters Foundation

Richard Chapin, the inventor and founder of the first commercial drip irrigation systems company (Chapin Watermatics Inc. circa 1960) in the United States, created the non-profit organization Chaplin Living Waters Foundation in 1999 in order to donate the *Chapin Bucket Kit* to developing countries by partnering with mission groups, relief organizations, and development agencies. The Bucket Kits are manufactured by Chapin Watermatics and consist of two drip laterals that are 50' long running from a water source of 5 gallons (bucket not included in the kit). Two other products are also offered, the *Super Bucket Kit,* which has a water source of 35 gallons with 10 drip laterals each 33' long, and the *1/4 Acre Kit,* which requires a minimum flow rate of 10 gallons per minute and has 20 drip laterals each 100' long.

According to its website, the foundation to date has donated Bucket Kits to over 2500 groups in 150 countries, including places in the Americas (e.g., El Salvador, Mexico, Honduras, Guyana, Haiti), Africa (e.g., Uganda, Burkina Faso, Kenya, Guinea), and Asia (e.g., Nepal, Cambodia, Thailand) [15, 16]. Chapin Watermatics Inc. was acquired by Jain Irrigation Systems Ltd, a multi-national irrigation company based in India, in 2006. As a result, besides the Foundation, Jain Irrigation Systems also distributes the Bucket Kits through sales. Chapin estimates that 15,000 - 20,000 Bucket Kits have been distributed to different organizations in Africa. Mission groups and non-profit organizations distribute these kits for $7 each, but this price is actually subsidized, because the retail value is $25 [17, 18]. USAID has also funded the distribution of Bucket Kits in Africa, and the Kenya Agricultural Research Authority (KARI) is evaluating the equipment.

In the dissemination process, Chapin Living Waters offers complimentary support systems in training resources and seminars, networking, and media promotion. They have instruction manuals; conduct workshops and seminars with development agencies and mission groups in the developing world to educate local agricultural professionals, extension workers, and development groups involved in agricultural projects; and maintains of a database of all their partner organizations. The goal is to build a large enough distribution network of Bucket Kits such that people in the developing world can contact local sources for information, assistance, and materials [16].

## 4.2 Netafim Inc.

Israel-based Netafim, the largest drip irrigation company in the world, mostly manufactures for commercial purposes but does sell one PDIK system for the developing world, called the *Netafim Family Drip System* (*FDS*). The FAO remarks that the Netafim FDS has the "appearance of a large-scale system that has been scaled down for use by smallholders rather than a system that has been designed specially for [the developing world] market" because the emitters, pipes, and filter equipment in this PDIK system are the standard parts found in their commercial systems [17]. Indeed, given that the Netafim FDS costs $150 and covers 1000 $m^2$, Netafim continues to target more affluent farmers. Netafim has already introduced systems in China and plan to market to 50 other countries, but there is little evidence of the viability of these systems. There has been some documented success in disseminating through NGOs in Africa, but not with a market approach in India. Netafim Irrigation India's Managing Director Zvi Feler speculates the reason for market failure is that the company is not equipped with enough internal structure to disseminate directly to "big numbers of extremely small land holdings" [8, p.4].

There is an interesting story that gives more insight into the company's approach to appropriate technology. In *Out of Poverty*, Polak details how he had attempted with no success to form a partnership with Netafim in order to jointly develop and mass market extremely affordable PDIK systems to millions of household farmers. Netafim responded:

> Poor farmers deserve the best equipment. Let's form a partnership to win big World Bank contracts in Africa. The World Bank can easily subsidize the cost of our drip-irrigation equipment to a price poor farmers can afford. This will allow them to use the best drip equipment in the world, just like rich farmers. Netafim's sales will increase, and IDE will gain access to World Bank funding to expand its poverty alleviation initiatives [12, p.39].

On the other hand, Polak believes companies can be viable by selling directly to the poor and do not need to rely on subsidies–in fact, he claims that demand for products far outstrips the possible number of subsidies large organizations can give, so in the long run, it is more equitable to design products to be simple and low-cost, so that all customers can be able to afford the actual value of technologies. As a result, after Netafim's rejection, he created the IDE drip kits. It wasn't until after IDE drip kits enjoyed two years of successful business that Netafim decided to make a competing product, the FDS kit [19].

To conclude this story: predictably, in 2002, Netafim and Ben Gurion University's International Program for Arid Land Crops (IPALAC) won the World Bank Global Market competition with a prize of $250,000 to distribute this system in Niger [20]. However, there is no available information about the results of this project. Overall, Netafim seems to not have developed any complementary system to disseminate their system besides relying on grants and non-profits.

## 4.3 International Design Enterprises (IDE)

IDE is an international non-profit that creates appropriate technologies in consultation and field test trials with communities. Their specialty focus is on technologies that give a high rate of return on investment, specifically irrigation systems and treadle pumps. According to their website, currently they have established programs in countries in Latin America (Nicaragua and Honduras), Africa (Burkina Faso, Ethiopia, Ghana, Mozambique, and Zambia), and Asia (Vietnam, Cambodia, Nepal, India, and Myanmar). IDE first developed PDIK systems in India and Nepal in 1995. Since then, their products have gone under multiple design iterations to fit different contexts and needs. Field test trials have been conducted in Sri Lanka, Bangladesh, and Vietnam [17]. Extensive socio-economic anaylsis of drip kit usage in India and Zimbabwe has been conducted [8]. Current PDIK systems that IDE offer include the following: *IDE KB drip* (consists of a water bag as the source, irrigates a 20 $m^2$, and costs under $5.), *IDE Bucket kit* (based on the Chapin Bucket Kit, uses a 20-L elevated bucket as the source, irrigates 50 $m^2$, costs $5), and *IDE Drum kit* (uses a 200-liter steel or plastic drum, irrigates 125 $m^2$, and costs $25).

IDE promotes these products through their Affordable Drip Irrigation Technology Intervention Program (ADITI). These kits are not just technologies in the IDE philosophy. Rather, these kits are sustainably integrated into local communities, so that members are active stakeholders and are engaged as the kits' local manufacturers, dealers, suppliers, users, technical repair experts. IDE also promotes innovative public marketing strategies on a massive scale. For example, in order to effectively target their market in India, IDE developed a mobile film truck that would play a Bollywood-esque movie that had a romantic plot with product placement of IDE's treadle pumps [12]. ci:grasp, an online information platform on offering solutions to climate change adaption that is developed by the Potsdam Institute for Climate Impact Research (PIK), estimates that 2,95,000 kits have already been sold. With ADITI kits, farmers can not only increase the biodiversity of their crops and cultivate year round, but also can reduce the water use by 30-60%, increase crop yields by 20-40%, and double the amount of possible irrigated area in places with constrained water resources [21]. In field trials in Nepal, a farmer can invest $26 to purchase a drip system, $15 for other costs, and family labor to increase an average income of $10 tenfold with drip irrigation (this increase is half of the GNP per capita of Nepal) [17].

Case studies in India and Zambia showed that the successes of the drip kits were influenced by a variety of factors: the type of kit used; types of crops grown; the attitude, skills, and socio-economic standing of the users; and the larger agricultural context of their community and region. The degree of increased income generated corresponded to the size of the kit: the smaller bucket kits created modest additional funds, but the larger systems produced as much as 60% of the annual income in extra funds [8, p.4]. In general, families with average or above wealth in both countries were the main beneficiaries of the drip kits because they could already afford to invest in this type of capital equipment. On the other hand, poor people either received kits from NGOS or could not afford to purchase any. It was also discovered that AMIT is not a purely market approach to dissemination of the systems because many costs were subsidized: its product and market development were funded by external grants, users only paid for the purchase of the technology but not the repair costs, and NGOS that help with the distribution process are not remunerated [8, p.6].

Out of the three manufacturers discussed in this section, IDE seems to be promoting the most sustainable approach by continually engaging directly with their users, designing the products as simple and affordable as possible, providing extensive technical training, aggressively marketing drip kits by appealing to their consumer base with aspirational and income-generating products, and conducting and documenting field studies. This complementary system is necessary for the successful dissemination of this type of appropriate technology because there are levels of poverty in targeted communities and cost vs. payoff is a strong deciding factor in whether or not a farmer will ultimately adopt the product.

# 5 User testing in Nicaragua

Because PDIK systems are designed to be implemented in the developing countries, a crucial part of this investigation is to conduct user testing fieldwork in order to understand the process of installation, identify advantages and disadvantages of different systems, and note if users made any modifications in order to improve the systems. For the purpose of this project, user testing also served the purpose of identifying which factors in the usability of the system should be investigated further through quantitative testing and analysis. In addition, the MIT D-Lab program emphasizes community engagement in all of its undertakings in order to build a true collaborative relationship that fosters creative capacity building and co-creation in the framework of participatory international development. As a result, this thesis focuses on the user experience and feedback of a specific community partner in the context of Nicaragua. This allows us to not only understand how PDIK systems function on the ground, but also to build capacity and relationships with the community partner so that users will ultimate take ownership of the PDIK systems and contextualize these products such that they are appropriate and practical. This investigation has been approved by the MIT Committee on the Use of Humans as Experimental Subjects (MIT COUHES).

## 5.1 Community partnership

### 5.1.1 Background

In order to conduct field testing of PDIK systems, we created a partnership with Grupo Fenix, whose relationship with D-Lab has been on-going for several years already. Grupo Fenix is a non-profit organization that focuses on renewable energy and sustainable development in the community of Sabana Grande, Department of Madriz, in Northern Nicaragua. Grupo Fenix stemmed from the Alternative Energy Sources Program (PFAE) at the National Engineering University (UNI) in Managua and it works to empower rural communities with community participation and investigation of appropriate, renewable energy technologies.

Founded by Susan Kinne, Grupo Fenix has worked with the rural community of Sabana Grande since 1999, originally to support income generation through manufacturing solar energy technologies like solar panels and solar cookers by land mine survivors from the Iran Contra War. Grupo Fenix often partners with universities around the world to foster cultural and technical exchange and empower community members to be problem solvers who can help solve challenges of making small-scale, sustainable, and rural production be ecologically and economically advantageous. [2]

Sabana Grande is located in one of the poorest regions in the country, with most people earning less than $1 a day. [3] It is primarily a small farming community with a population of 1700 people. The biggest problem that it faces is that the area is 80% deforested, due to unsustainable agricultural practices and a reliance on firewood as the primary source of fuel. It also faces water supply problems, in part because the deforestation has caused the soil to erode and lower the water table. Additionally, the local water wells that have been donated by UNICEF cannot be used for agricultural purposes due to donor-imposed limitations. Water supply problems are further exacerbated by the fact that the region undergoes two distinct wet and dry seasons. In general farmers will only plant during the rainy season because they depend on rain-fed irrigation methods to help optimize the growth of the plants

In 2006, Grupo Fenix purchased 35 acres of mostly degraded farmland for communal use, named "Solar Mountain," within the community of Sabana Grande. The objective has been for the community members to assume ownership of rehabilitating the land so that they can not only enjoy a healthier community, but also generate income for their efforts. In particular, a core group of fifteen community members has organized together into the Agro-Ecological Solar Promoters (AESP) to take responsibility for designing and implementing reforestation and sustainable agriculture projects on Solar Mountain. Over the past six years, the AESP has planted over a thousand maya nut trees, created a small tree nursery for coffee plants, and has started to plant local medicinal plants and fruit trees such as bananas and

[2]Personal communication with Ms. Kinne, January 2011
[3]Personal communication wth Ms. Kinne, January 2011

avocados. Local community members have also built a solar water tank collector on-site at the communal land to easily access the water that is needed in order to irrigate the trees and plants. Given the large scope of the reforestation efforts, the community partner members have been interested in exploring the feasibility of drip irrigation in order to have better management of water delivery to the plants and trees.

### 5.1.2 Project role

This community between MIT D-lab and Grupo Fenix has been well established for several years because of on-going collaborative projects with D-lab's Innovations in International Health program and annual student fieldwork trips arranged by the D-Lab Energy class. As a result, in the context of this investigation, this on-going relationship has proven to be critical in gaining and fostering the respect and trust of user testing participants to facilitate the working partnership.

From October to December 2011, regular communication with Grupo Fenix was undertaken in order to determine if Sabana Grande would be an appropriate test site for pilot PDIK systems implementation in January 2012. Ms. Kinne noted that the objectives of this investigation complemented the mission of Grupo Fenix and the introduction of PDIK systems could be an interesting experiment in order to determine if sustainable agriculture could flourish during the dry season with minimal consumption of water. This experiment would help resolve concerns about the current large amount of water usage that is needed for irrigation and also the lack of ability to grow in the dry season. Grupo Fenix and we determined that the Solar Mountain site was ideal because it is already home to many sustainable projects and community members enjoy learning and exploring new ideas of permaculture and agro-forestry on communal land, in part because the risk of crops failing from new experiments on their land is minimized. As a result, Grupo Fenix agreed to recruit study participants based on the following qualities: being deliberate, thoughtful, concerned, cooperative, and interested in learning and using PDIK systems. These study participants would form a focus group that would install the systems, maintain the systems throughout January, be interviewed about their experience with the systems, and continue the follow-up work after the field testing period concluded. By the end of December 2011, 16 participants were identified, comprising a group of 4 men and 12 women, ages 23-45, all either Grupo Fenix staff or AESP members who regularly are involved with reforestation and solar energy projects.

## 5.2 Installation process

Over a course of the second week in January 2011, two IDE drip kit systems and one Chapin Super Bucket Kit were installed on a prepared 30 m x 10 m plot of open land on Solar Mountain. The installation process for each system involved unpacking the systems and itemizing the components, identifying and acquiring any additional necessary components, and planting seeds to gauge efficacy of the systems on plant growth. Weve planted cucumber, chayote, pumpkin, margarita flowers.

In unpacking the two different types of kit, it was found that the overall design of the IDE kit was simpler than that of the Super Chapin Bucket Kit. It is important to note that because both instruction manuals were in English, I provided translation in Spanish to facilitate the installation process, and as a result, the installation process was influenced by my clarifications and previous experience with installation of PDIK systems.

The IDE drip kit included the following components:

1. A reinforced plastic bag to store water
2. A manifold with a built-in small hand pump that would connect the water source to the system of submain and drip laterals
3. A filter
4. An integrated system of submain, T-connectors, and drip laterals pre-perforated with straw emitters

5. A one page instruction manual

Users needed to construct a stand to elevate and support the water bag to achieve the necessary pressure head and build wooden stakes to secure and hold the drip lines parallel to each other.

The installation process of the IDE kit lasted 1.5 hours and is illustrated in Figures 5.1 to 5.5. In general, users agreed that the installation process went quickly because there were minimal components and the most complicated component–the integrated system of the submain and drip laterals–was already set-up. Issues that users noted were that some of the straw emitters had to be re-inserted into the perforated holes because they were prone to falling out. The material of the drip lateral was thin enough that the sharp ends of the emitters could create undesired punctures while the system was still packaged because additional holes that were not pre-manufactured in the drip tape were discovered. In addition, the pump that was used to start the flow rate from the water bag to the rest of the system often times was not reliable because no water would flow because of the build up of air in the tubes.

**Figure 5.1:** Opening the IDE drip kit. Photo: Susan Kinne (2012)

**Figure 5.2:** Straightening the tape. Photo: Susan Kinne (2012)

**Figure 5.3:** Filling the water bag with water. Photo: Susan Kinne (2012)

**Figure 5.4:** Pumping the system to start the flow rate. Photo: Susan Kinne (2012)

**Figure 5.5:** Water dripping out of emitter after successful installation. Photo: Susan Kinne (2012)

The Chapin Super Bucket kit included the following components:

1. A roll of submain
2. Tubes to connect submain and drip laterals
3. A filter
4. A roll of Pre-perforated drip tape
5. A multi-page instruction manual
6. Male and female fittings to create a seal in the bucket
7. A puncture device to perforate the submain

Users also needed to provide the same components that the IDE drip kit lacked (the wooden stakes and elevating stand for the water container), as well as provide a 33 gallon bucket to act as the water container.

Users found this installation process to be much more complex and confusing than that of IDE drip kit because none of the components came pre-assembled. The steps of the installation process are detailed in Figures 5.6 and 5.11. As a result, the basic installation lasted for three days and took an additional three days to debug. The complexity stemmed from the fact that users must entirely size and assemble all of the components together. Unlike the IDE kit, the Chapin Super Bucket Kit has not been pre-sized, so it is up to the users to determine the dimensions of the submain and drip laterals and then create perforations in the submain to connect these components together. In addition, the bucket must be drilled to make space for the fittings and filter. Three users expressed concern that the system installation is not intuitive and, because of the language barrier with the manual, they would have given up in frustration and discontinued the installation process. All users agreed that the slits on the bottom of the Chapin drip laterals was a better design than the straw emitters of the IDE kit because it eliminated the problem of the emitters frequently falling out and emitters needing to be adjusted manually to improve drip aim. In addition, all users agreed that the drip laterals of the Chapin Super Bucket Kit were much more durable than the IDE kit and did not create problems of unnecessary perforations.

**Figure 5.6:** Cutting a drip lateral that is 10 m long. Photo: Susan Kinne (2012)

## 5.3 Debugging

Both systems had some flaws, so the study participants debugged problems and modified the systems until the flaws were resolved. The IDE kit drip tape's thickness was measured to be 0.1 mm and was easily punctured accidentally by other emitters when bundled in the packaging or stray twigs next to the installed drip tape sometimes caused perforations. Because the holes typically were small and shallow, community members resolved the problem with a simple patch of applying a small dab of PVC glue over the hole.

On the other hand, the drip tape of the Chapin Super Bucket Kit wast 0.5mm in thickness, and this thickness proved to make the necessary perforations along the submain to insert the connecting tubing into the drip laterals difficult process. Jorge, the community member in charge of assembling the submain and drip lateral system, remarked that creating

**Figure 5.7:** Laying the drip lateral. Photo: Susan Kinne (2012)

**Figure 5.8:** Getting ready to puncture submain. Photo: Susan Kinne (2012)

**Figure 5.9:** Creating a table to elevate the 33 gallon bucket. Photo: Susan Kinne (2012)

**Figure 5.10:** Filling up the feeder bucket. Photo: Susan Kinne (2012)

**Figure 5.11:** Water dripping out of slit on the bottom side of the lateral. Photo: Susan Kinne (2012)

the holes with the puncture tool to a diameter large enough to fit the connecting tube was challenging and time consuming. He spent an hour making the holes the correct size because the material was very stiff and difficult to puncture, even with the provided tool. After the system was assembled completely following the instructions accordingly and the study participants added water to the bucket to run the system, the focus group discovered that the punctured holes had no seal at the connection to prevent leakage. This proved to be a challenging problem to solve, and it took four iterations over a course of three days to debug, understand, and solve the problem. These iterations are detailed below:

1. Originally, community members thought that the same patch fix with PVC glue that they had administered to the IDE kit would be sufficient to seal the holes. Unfortunately, the gaps proved to be too large and deep in comparison, and thus the PVC glue could not bond thickly enough to create a level seal flush around the connecting tubing. In addition, much of the PVC glue spots dabbed onto the submain disintegrated or fell off because the water flow rate through the submain created enough force to disturb

the sealant bonds.

2. Community members then brainstormed and decided to attempt to seal with a thicker sealant, a silicone adhesive. Although the leakage decreased, silicone still could not provide a tight enough seal.

3. Community members decided to try an alternative to the provided 0.25" diameter connector tubing and instead create home-made connectors with teflon, two inch sections of PVC pipe with a 0.5" diameter, and rubber sections cut from old bike tubes. All of these materials were already available in the community tool shed, so Jorge and Erika, the project manager of Grupo Fenix, decided to create a simple sketch model. The PVC pipe would be the connector, teflon would be inserted in the hole of the submain, and the PVC pipe and the drip laterals would be secured to the submain with the rubber, essentially creating a T shaped connector. Hilario and Julian, both coordinators of the AESP, supported the sketch model because rubber provided a completely water-tight seal and all the materials were already available at Solar Mountain, but after Jorge translated the sketch model into a fix for the entire length of submain, the increase of diameter of the tubing caused a significant enough decrease in the water flow rate that no water was flowing into the drip laterals at all.

4. After the third iteration, community members agreed that although the previous iterations were useful in gaining insight about the limitations of the connection between the submain and drip laterals, these attempts resulted in wasting valuable materials, and on top of it, the outcome from the third iteration was a disaster because the seeds were already sprouted and direly needed irrigation to survive. After a discussion, community members decided that in the interest of time and quality, they should replace the Chapin submain immediately by purchasing commercially available submain and T connectors at the local hardware store. These items in total cost $65, a price that is normally a steep investment for one farming household, but in this situation costs

were subsidized by project funds from the MIT Public Service Center Fellowship. Once installed, community members all agreed that it was worth the upgrade because there were no longer any functional or leakage problems.

## 5.4 Social Impact

Overall, the introduction of drip irrigation kits to Solar Mountain had a strong social impact on the community. Community members were able to successfully plant and see results in the dry season (in which insufficient water supply was often a problem) for the first time because drip irrigation permitted them to sustain crops with a minimal amount of water. Therefore, this field testing trial sparked an interest in many community members to further learn about permaculture and other sustainable farming techniques, as shown in Figure 5.13. In addition, since the focus group participants consisted mostly of women, they developed the confidence to grow vegetables, do farming and also use technology, activities that traditionally had been reserved for men in this society. In particular, focus group members Mayra, Erika, Nimia, and Corinna voiced wishes to purchase a family sized PDIK system of their own to plant a vegetable garden at home.

Five months after the field testing trial, fruits and vegetables matured and the community members were able to consume and sell the fruits of their labors. Nimia declared,"Drip irrigation is incredible. As a community, we have learned how to create income in the dry season, which was unheard of before unless you could afford to flood irrigate your plants."[4] Instead of commuting 40 miles daily to purchase vegetables and fruits, community members could locally purchase produce in Sabana Grande. Figure 5.12 shows Mayra holding a melon that was grown in the drip irrigation plot on Solar Mountain. This access to local produce promoted a more balanced diet in a community that primarily consumes starches, because vegetables and fruit are too expensive.

[4]Interview with Nimia Lopez, April 30, 2012.

**Figure 5.12:** Mayra holds a freshly picked melon from the vegetable garden that is irrigated by the IDE drip kit. Photo: Susan Kinne (2012)

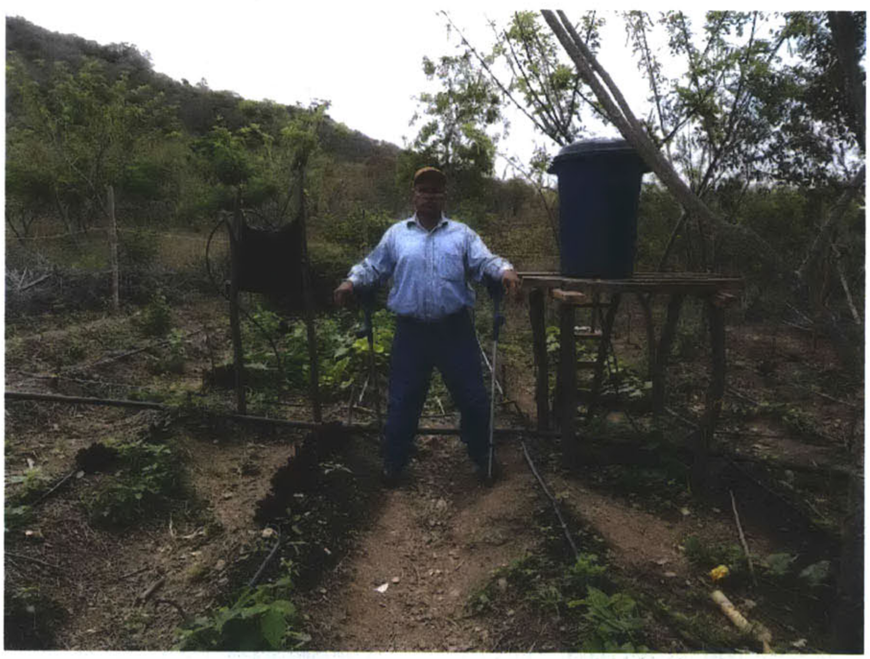


**Figure 5.13:** Many community members have come to visit and learn about drip irrigation at Solar Mountain. Photo: Susan Kinne (2012)

# 6 Laboratory testing

Inspired from the problems that arose during the user testing experience in Nicaragua, this investigation seeks to answer the following three key questions:

1. What is the performance of the drip irrigation systems?
2. What are the material strengths of the drip tape?
3. What is the rate of clogging of the filter?

## 6.1 Emitter discharge performance

The primary measure of potential performance of drip irrigation systems is the uniformity of water distribution, also known as Emission Uniformity (EU) (Keller and Bliesner, 1990), and is a combination of factors such as the water supply's pressure head, any topological elevation differences present on the plot of land, friction losses in the pipe distribution network, and emitter discharge characteristics. However, EU does not take into account factors such as type of equipment or cropping conditions, so it has been proposed by Keller and Keller (2003) that a more relevant measure of performance for a small PDIK system is the Coefficient of Variation Uniformity (CvU) of the individual emitter discharges from the field test data because it takes into consideration variability within the entire population of emitters.

The equation for Coefficient of Variation Uniformity is as follows:

$$CvU = 100(1.0 - \frac{sd}{q_a}) \tag{1}$$

where sd is the estimated standard deviation of the emitter flow catch rates (lph) of the population and $q_a$ is the average rate (lph) of the emitter flow rate for the population.

The relationship between the Emission uniformity and Coefficient of Variation Uniformity is as follows:

$$EU \approx 100 - 1.27(100 - CvU) \quad (2)$$

Keller and Keller (2003) recommend the following performance criteria ranges CvU for PDIK systems suitable for small household farming plots:

- CvU above 88% is excellent;
- CvU between 88% and 80% is good;
- CvU between 80% and 72% is fair; and
- CvU between 72% to 62% is marginally acceptable.

The average rate of the emitter flow ($q_a$) can be determined experimentally by measuring the ratio of volume displaced by each individual emitter ($v_i$) over the total time the system takes to completely emit all the water that was orginally stored in the water source container ($t$), as related in the following equation:

$$q_a = \frac{v_i}{t} \quad (3)$$

### 6.1.1 Experimental set-up

Given that the main criterion for performance testing is the flow rate from each individual emitter as referenced in Equation (1), the most important factor in this test was to create an experimental system that would capture the flow rate of each individual flow rate. The experimental set-up is shown in Figure 6.2. Testing for the Chapin Bucket Kit was conducted in the MIT Pappalardo Undergraduate Teaching Lab (Room 3-030) and testing for the IDE drip kit was conducted in the alley located adjacent to the D-lab building (E34). These testing spaces were chosen because they were available for testing purposes and also whose ground surface was as level as possible to create the ideal uniform flow rate environment.

For the Chapin Bucket Kit, the experimental set-up is represented in Figure 6.1. A scaled down version of the Chapin Super Bucket Kit that had been installed in Nicaragua was implemented for the test. The set-up dimensions involved a 5 gallon bucket (as opposed to the 33 gallon bucket in the field) elevated 1 m off the ground with the use of a window sill and four 5.7 m-long drip laterals (as opposed to ten 10 m-long drip laterals). A Solo Squared™plastic bowl with the volume capacity of 591 mL was placed under each emitter, for a total of 44 emitters, in order to catch the volume of water displaced by the emitter. Up-side down lab stool chairs were placed at the ends of the drip laterals and sub-main so that the system would lie flat on the group for uniform flow throughout the entire piping system.

**Figure 6.1:** The experimental set-up of testing emitter flow rate performance for the Chapin Bucket Kit. Photo: Lisa Johnson (2012)

The reasons for testing a scaled-down Chapin Bucket system are as follows:

1. Chapin Watermatics offers both the regular Chapin Bucket Kit designed for a low-income household plot (25 $m^2$) and the Chapin Super Bucket Kit designed for a larger sized plot designed a medium-income farm plot (100 $m^2$). Both systems use the same

components, so there is no material change in testing a scaled-down version.

2. The Chapin Bucket Kit installation manual includes options for different configurations: 2 rows (2 x 15 m drip laterals), 4 rows (4 x 7.5 m drip laterals), and 6 rows (6 x 5 m drip laterals). The 4 row configuration was selected for the emitter testing because not only are the dimensions typical of a family garden plot, but also can be used as a basis of comparison because the IDE drip kit has 4 rows.

3. All study participants in the Nicaragua field testing expressed that if they had to choose between two options which system to install on their plots, they would choose the IDE kit system ((25 $m^2$) because of its relevant size.

4. Along similar lines of which Chapin system is more appropriate for a small plot farmer, a 33 gallon bucket is very difficult to acquire for a typical family in Nicaragua. 5 gallon buckets are much more commonplace because people generally do not have household plumbing and must go to a local well to obtain water with 5 gallon buckets.

For the IDE drip kit system, the experimental set-up is illustrated in Figure 6.2 . The water bag containing 5 gallons of water was suspended 1 meter above the ground with the use a ladder and two cable ties for support. The sub-main was elevated 2 inches above the ground with the use of 2" x 4" pieces of wood, angle iron, and cable ties to remain parallel to the ground. Solo Squared ™plastic bowls (591 mL) were similarly placed underneath the IDE drip tape to catch the water displacement. A block of wood was placed over each drip lateral to anchor the system in a stabilized manner.

**Figure 6.2:** The experimental set-up of testing emitter flow rate performance for the IDE drip kit. Photo: Lisa Johnson (2012)

Figures 6.3 through 6.7 depict the experimental procedure that was used for both systems. First, 5 gallons of water was poured in the water source (5 gallon bucket for Chapin system, 5 gallon water bag for IDE system), and this level was verified by using a ruler to measure the level of water present, as shown in figure 6.3. Once all the components were installed accordingly to the instruction manual, flow rate was started. The IDE system was pumped to start the water to flow from the water bag to the piped network, as shown in figure 6.4, while the flow started automatically from the Chapin system once all the parts were installed together (no pump is included in this design). Once all the drip laterals had water flowing, the IDE emitters and Chapin and IDE drip tape laterals were adjusted, such that the water would be directed into the plastic bowls and there would be no loss of water emitting onto the ground, as shown in figure 6.5. The droplets emitted could be observed, as shown in figure 6.6, and would pool into the plastic bowl until the water source was nearly empty. The height of the water displaced was measured with a ruler, as shown in figure 6.7, and then poured in a 250 mL graduated cylinder in order to determine the total volume of water displaced by each emitter.

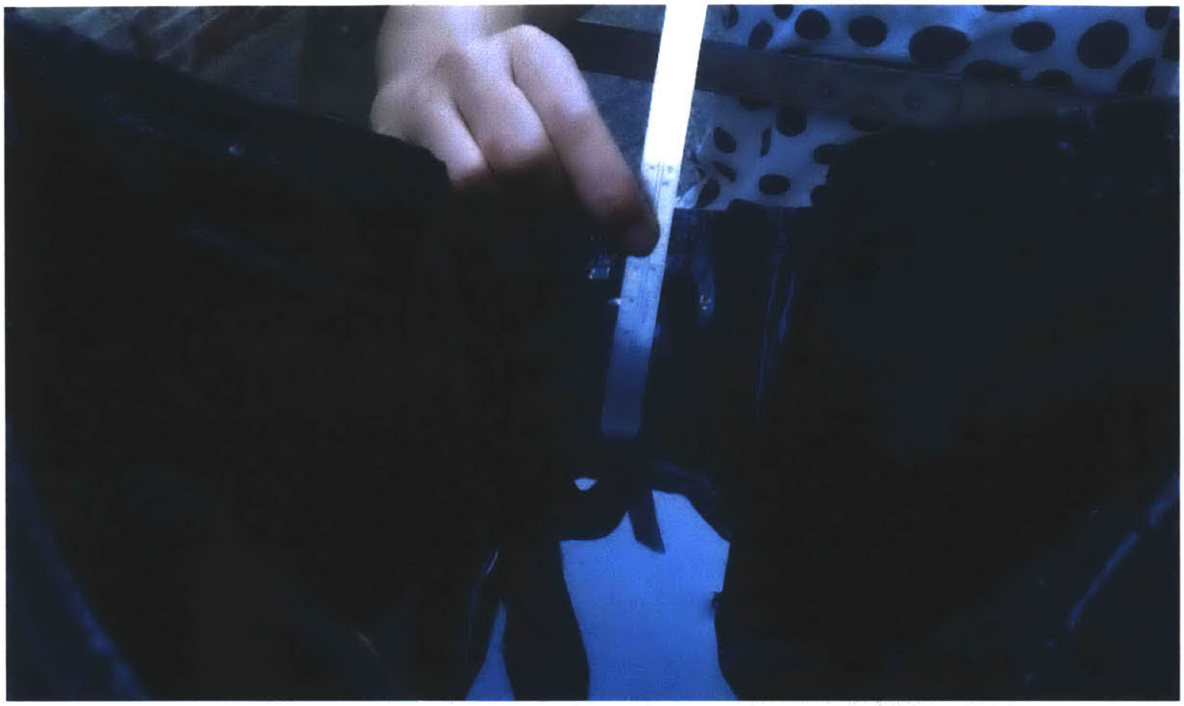


**Figure 6.3:** Measuring the level of the water in the water bag, determined to be 5 gallons. Photo: Lisa Johnson (2012)

**Figure 6.4:** Pumping the system to start the flow of water from the water bag to the drip laterals. Photo: Lisa Johnson (2012)

**Figure 6.5:** Adjusting the emitters such that the water flow is directed into the plastic bowls. Photo: Lisa Johnson (2012)

**Figure 6.6:** An emitter producing droplets into the plastic bowl. Photo: Lisa Johnson (2012)

**Figure 6.7:** Measuring the height of the water displaced with a ruler in order to determine total volume of water displaced by each emitter. Photo: Lisa Johnson (2012)

A set of 10 experimental data points from one drip lateral length of the IDE drip system was quadratically fitted to determine the conversion between height of the water to corresponding volume of water, as shown in figure 6.8.

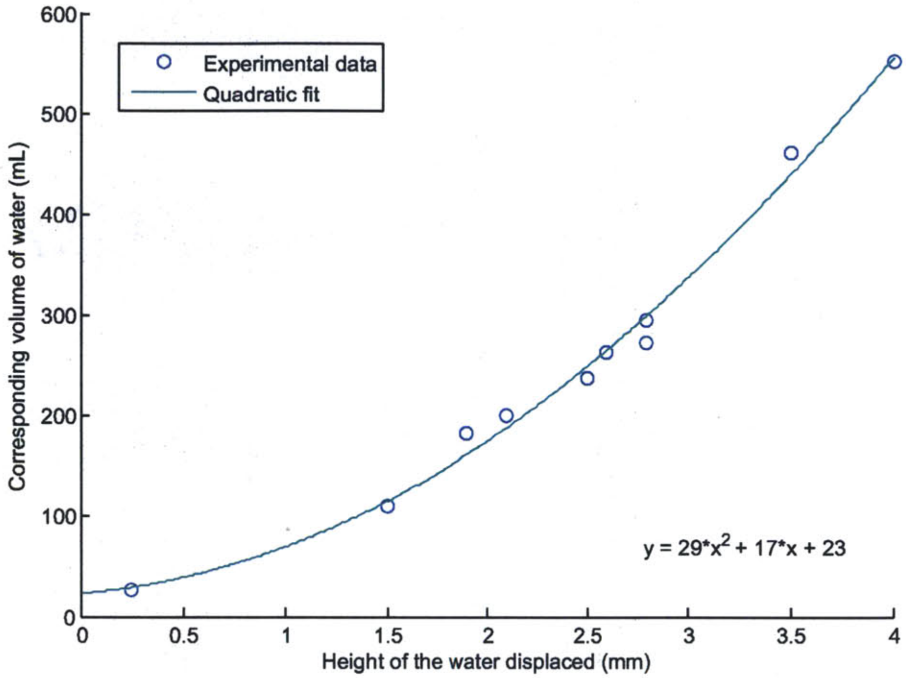



**Figure 6.8:** Determining the volume of water displaced by the emitter from height measurements using a quadratic fit.

A quadratic regression formula relating height of the water dispaced in the bowl to volume of the water displaced was generated as following:

$$V = 29h^2 + 17h + 23 \tag{4}$$

where V is the volume and h is the height of the water in the plastic bowl.

### 6.1.2 Results

The individual emitter flow rates (lph) for both Chapin Bucket Kit and IDE drip kit were calculated using Equations (3) and (4). Figures 6.9 and 6.10 display the flow rates for each emitter for the two systems. Rows A to D represents the rows from left to right of the system. The emitters closest to the submain extending all the way down to the end of the drip lateral are ranked 1-11. Both figures show that in general, flow rate decreases along the length of the drip lateral, but the decrease is non-linear. Both systems show a trend that after an emitter decreases in flow rate, the following emitter will produce a slight increase in flow rate. The Chapin Bucket Kit displays a more uniform emitting behavior, while the IDE drip kit displays more pronounced spikes of emitter flow throughout the system. For both systems, all the rows except for Row B have relatively the same magnitude of average flow rate. This behavior might be caused by the fact that in both system Row B is closest to the main and receives more of the fraction of water that is flowing from the bucket or water bag.

More precisely, the values of emitter performance parameters were calculated using Equations (1) and (2) and are summarized in Table 6.1. The Chapin Bucket Kit had higher values for all the emitter performance parameters compared to the IDE drip kit. The Chapin Bucket Kit's average emitter flow rate was 2.76 lph with a standard deviation of 0.915, whereas the IDE drip kit had an average emitter flow rate of 1.93 lph with a standard deviation of 0.857. In other words, the flow rate of the Chapin Bucket Kit was faster by 30% and is most likely attributed to the fact that there was leakage at each connector between the sub-main and drip lateral because there was not sufficient enough seal. The Coefficient of Variation Uniformity for the Chapin Bucket Kit was 66.8% and for the IDE drip kit was 55.6%. Thus, the Chapin Bucket Kit system falls within the CvU range "marginally accetpable" as mentioned in Section 6.1. However, the IDE drip kit's CvU falls below this range. Possible reasons for the IDE kit's low CvU value are that the concrete ground in the testing site near D-lab was not level enough (the dramatic spike of 4.5 lph at emitter in Row A, no. 10 corresponds to an upward ridge of concrete at the emitter site). Furthermore, the emitter straws of the IDE system consisted of different lengths and had to be adjusted several times throughout the course of experiment so that water would drip out, so the longer the emitter straw, the faster the flow rate was due to capillary action.

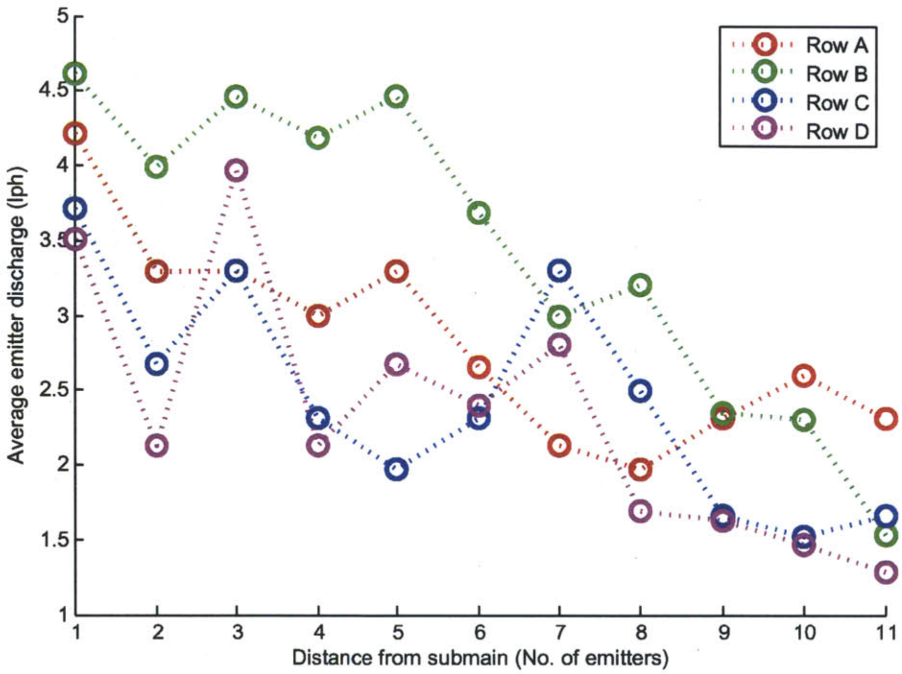



**Figure 6.9:** Experimental results of the average emitter discharge (lph) for each emitter in the Chapin Bucket kit.

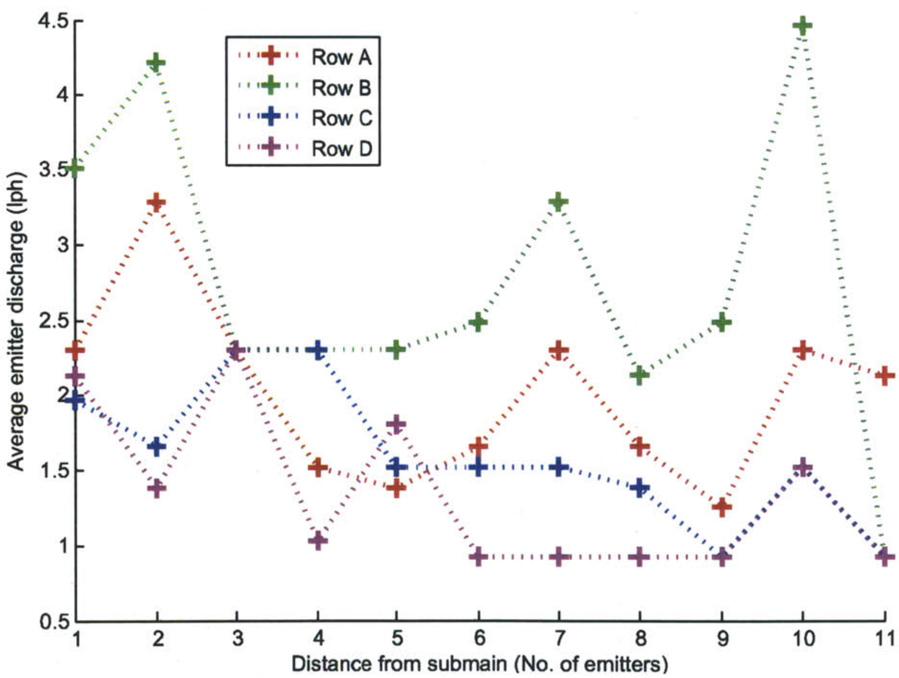



**Figure 6.10:** Experimental results of the average emitter discharge (lph) for each emitter in the IDE drip kit.

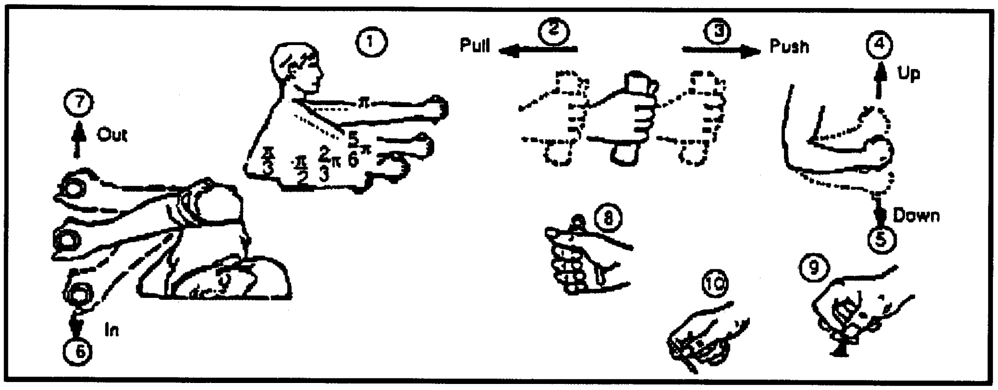
| | Chapin Bucket Kit | IDE drip kit |
|---|---|---|
| standard deviation of emitter flow rate, sd (lph) | 0.915 | 0.857 |
| average emitter flow rate for the system, qa (lph) | 2.76 | 1.93 |
| Coefficient of Variation Uniformity, CvU (%) | 66.8 | 55.6 |

**Table 6.1:** Summary of emitter performance parameters

## 6.2 Material strengths and human factors

In the field testing, users noticed a couple of material qualities for both PDIK systems. First, people could accidentally and easily puncture the IDE drip tape when unpackaging the kit and unraveling the drip tape system because the sharp tips of the emitters could punch through other sections of the tape. Second, it was difficult to put the necessary punctures into the Chapin tape in order to connect the entire drip system together. Third, users were concerned about whether the tape could be over-pulled because people used a strong pulling motion in order to secure drip laterals to wooden stakes so that the tape would lie flat on the soil. To respond to these concerns, laboratory testing was conducted in order to determine the force required to puncture through the tape, as well as the tensile stress characteristics of the tape and then compared to available data of human performance capabilities.

The National Aeronautics and Space Administration (NASA) has compiled data of human performance capabilities, include that of human muscle strength. In particular we are most interested in the pull and down force generated by the arm [22]. Figure 6.11 depicts the hand and thumb strength for 5th Percentile Males. To be conservative, we choose data with the degree of elbow flexion as 180 degrees. Thus, the maximum force that is generated by the pulling motion is 231 N and the maximum down force is 75 N for humans. If the laboratory measurements for the puncturing force and tensile force are larger than these human factors values, then these concerns can be resolved.




| (1) | (2) | | (3) | | (4) | | (5) | | (6) | | (7) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Degree of elbow flexion (rad)** | **Pull** | | **Push** | | **Up** | | **Down** | | **In** | | **Out** | |
| | L** | R** | L | R | L | R | L | R | L | R | L | R |
| π | 222 | 231 | 187 | 222 | 40 | 62 | 53 | 75 | 58 | 89 | 36 | 62 |
| 5/6 π | 187 | 249 | 133 | 187 | 57 | 80 | 80 | 89 | 67 | 89 | 36 | 67 |
| 2/3 π | 151 | 137 | 116 | 160 | 76 | 107 | 93 | 116 | 89 | 98 | 45 | 67 |
| 1/2 π | 142 | 165 | 98 | 160 | 76 | 89 | 93 | 116 | 71 | 80 | 45 | 71 |
| 1/3 π | 116 | 107 | 96 | 151 | 67 | 89 | 80 | 89 | 76 | 89 | 53 | 76 |

**Figure 6.11:** Hand and thumb strength, 5th Percentile Male Data (N). Image: NASA (1995) [22]

### 6.2.1 Experimental set-up

To conduct materials testing, the Instron machine in the 2.002 Materials Teaching Lab was used. The Instron machine collects testing data through strain-guage load cells and servo-control systems. It is depicted in Figure 6.12. Initial gauge lengths of 52 mm for drip tape samples were used and then pulled 100 mm and punctured, as depicted in Figures 6.13a and 6.13b. The testing conditions were pre-set by the machine.

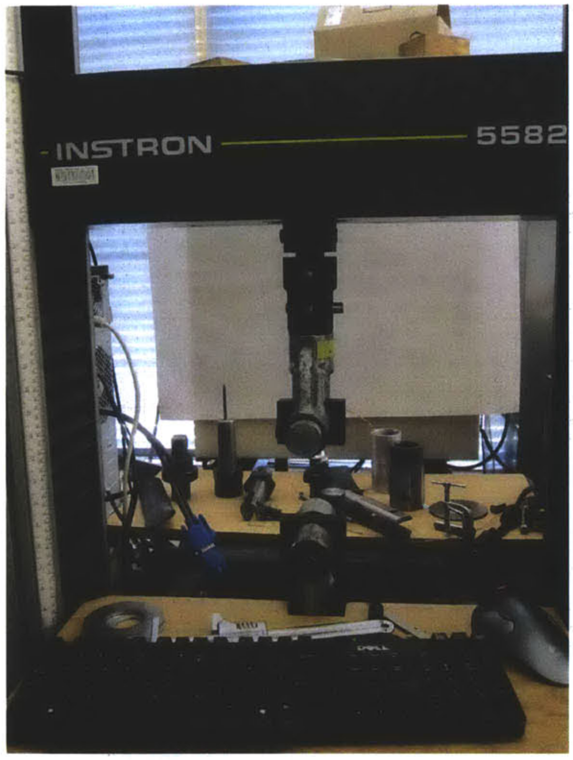
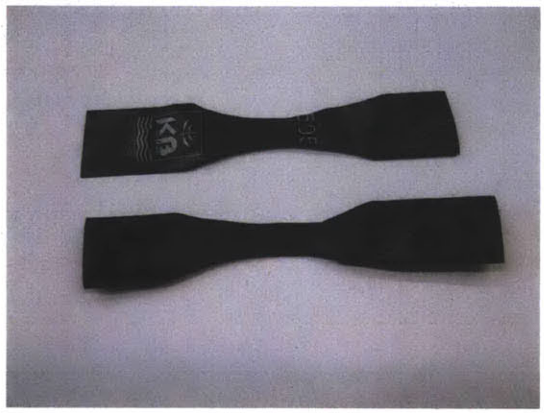



**Figure 6.12:** Experimental set-up for materials testing

**(a)** Relaxation in drip samples after tensile stress test.



**(b)** Drip samples after puncture test.

**Figure 6.13:** Materials testing

### 6.2.2 Results

Both the Chapin and IDE drip tape were subjected to tensile and puncture tests and the results are represented in Figures 6.14 and 6.15. The maximum loading before deformation starts occurring for the Chapin drip tape is 350 N and for the IDE drip tape is 75 N. As mentioned previously, the maximum force that is generated by a person pulling is 231 N. We can conclude that while the Chapin drip tape will not be over-stretched by manual methods in any situation, the IDE drip tape on the other hand may be over-stretched since maximum pulling force of the material is 32.5% of the maximum human force. Similarly, for the puncture test the IDE drip tape will be punctured with a force of 40 N, which is

53.3% of the maximum downward force generated by humans, at 75 N. In other words, the IDE drip tape is resistant to external loadings, but this may be because the manufacturers decided that the trade-off for thinner LDPE material was worth the reduced cost of material. The Chapin drip tape punctures at 75 N, but this is a borderline case because the value of the maximum downward force is from the 5th percentile of male data. In other words, it is indeed difficult to puncture through the Chapin drip tape, even though this action is necessary for the kit installation. It is recommended that the manufacturers of the Chapin drip tape investigate the possibility of substituting for a similarly durable material but is more user friendly to puncture to aid the installation process.

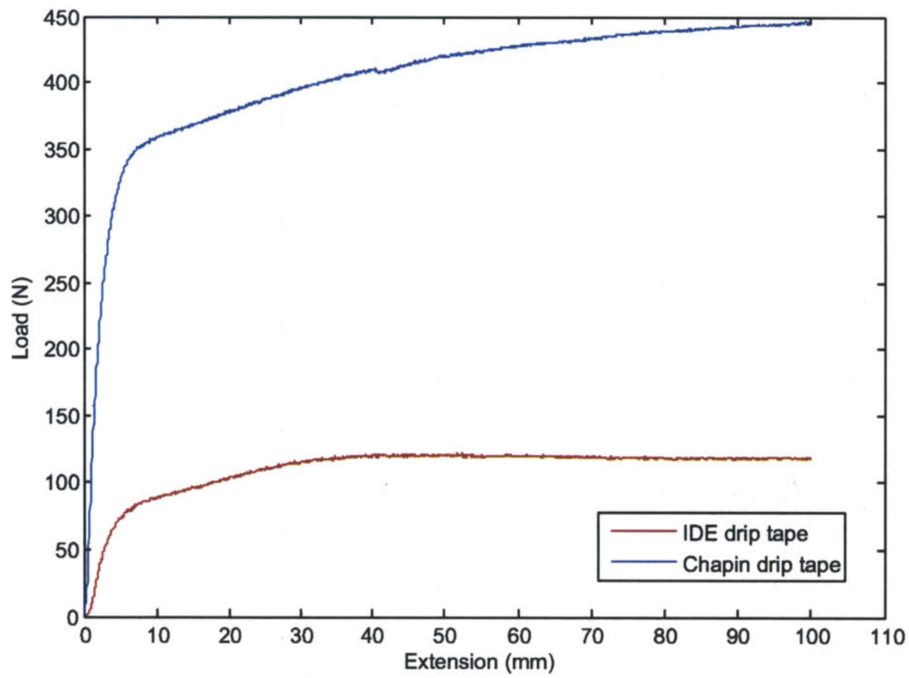



**Figure 6.14:** Tensile test

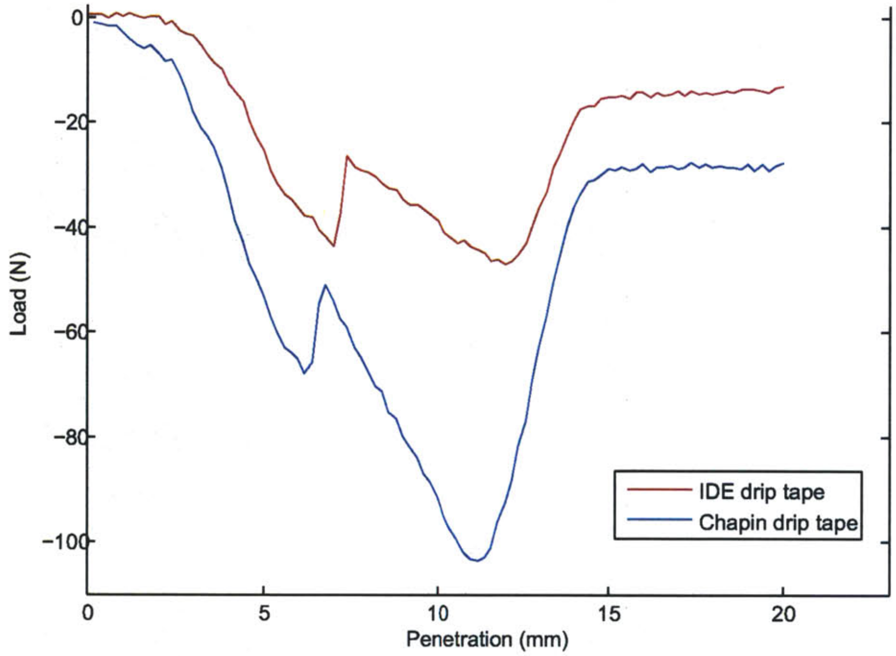



**Figure 6.15:** Puncture test

## 6.3 Filter clogging

The grain size of soil particles that can pass through the filters (thus potentially being able to clog the PDIK systems) is determined by sieve analysis. Sieve analysis consists of first pouring a soil sample onto the top layer of a series of sieves with different hole sizes and then agitating the stacked sieves in order to create separation of the particle size of the sample. The sieves have square holes, and the size criterion is based on round soil particles falling through the holes. Sieves are classified with sieve numbers, which are related to the size of the holes in the mesh. The larger the sieve number, the smaller the hole is. In sieve analysis the sieves are stacked from smallest sieve number to largest sieve number. The sieve sizes are selected based on either a standard laboratory set or perceived distribution of grains. After the test is conducted, the sieves can be separated and the mass of the retained particles on each sieve can be determined.

The number of layers of particles in a sieve can give a reasonable indication of whether an individual particle can have access to the holes of the sieve. The mass of a single layer of spherical particles on a given sieve ($M_{SL}$) can be determined from the following equation:

$$M_{SL} = 0.52\frac{\pi D_s^2}{4} D_p G_s \rho_w \tag{5}$$

where $M_{SL}$ is the mass of a single layer of spherical particles on a sieve, 0.52 is the volume ratio of a sphere in a cube, $D_s$ is the diameter of the sieve, and $D_p$ is the diameter of the particle or sieve opening.

The percent of the mass of the retained particles on each sieve to the total mass of the sample can be determined by the following equation:

$$\%M_{p,i} = \frac{M_t - M_{p,i}}{M_t} \times 100 \tag{6}$$

where $M_{p,i}$ is the mass of the particle size of a given sieve i and $M_t$ is the total mass of the soil sample.

### 6.3.1 Experimental set-up

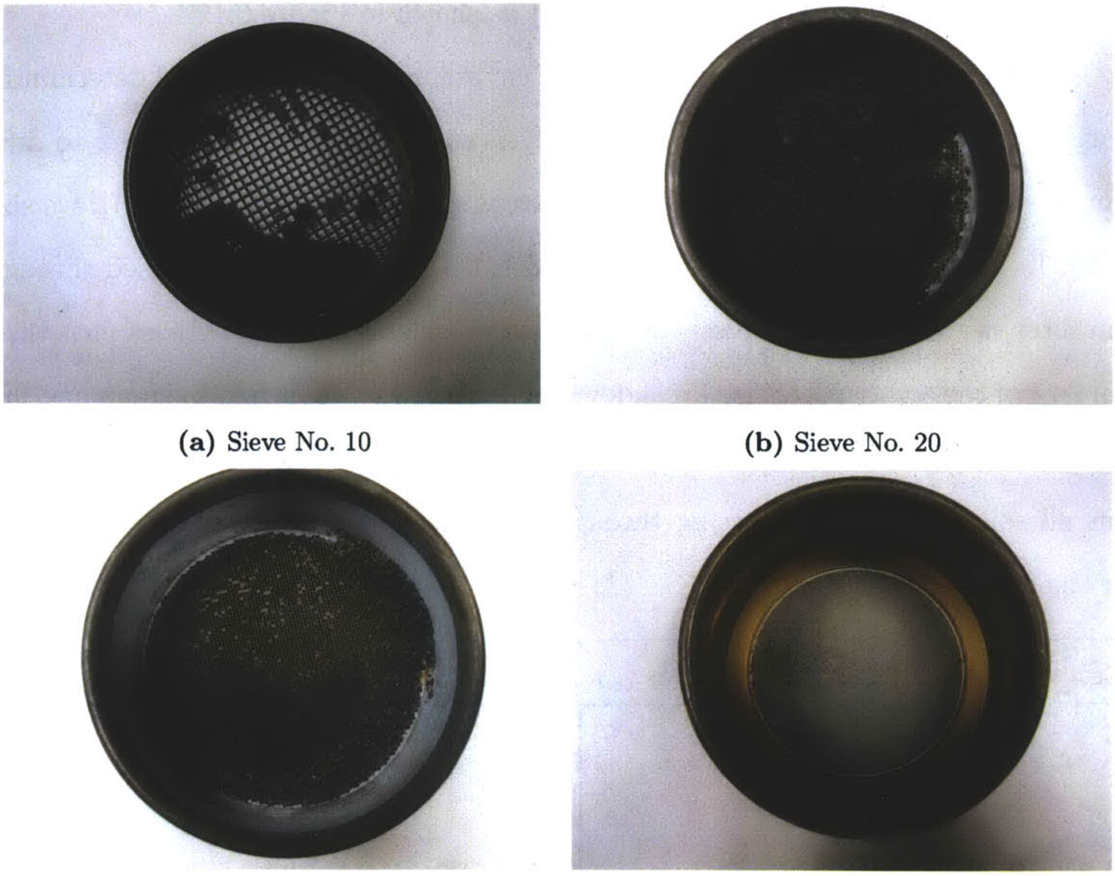
The experimental set-up of the sieve analysis is depicted in Figure 6.16, with the stacked sieves, soil sample, dome-shaped filter of the Chapin Bucket Kit, and cylindrical-shaped filter of the IDE drip kit.

To determine the appropriate sieve sizes for the test, both filters from the Chapin and IDE drip irrigation systems were examined and compared to analogous sieve sizes by inspection. It was determined that for the Chapin Bucket Kit filter the corresponding sieve number is 42 with a hole size of 0.35 mm, and for the IDE drip system the sieve number is 120 with a hole size of 0.125 mm. Six sieves were selected for the test in numbers 10, 20, 30, 42, 45, and 120. The soil sample was collected from the MIT Macgregor dormitory courtyard.

The collected soil sample was first lightly mixed. Then 26.2 grams of the soil sample was placed on the top sieve. The entire system was shaken with a paper covering for 10 minutes, as depicted in Figure 6.16. Afterwards, the sieves were separated and the mass of each retained sample was measured, as shown in Figure 6.18.

**Figure 6.16:** The experimental set-up of sieve analysis in order to determine the particulate matter that will pass through the filters of the PDIK systems.

**Figure 6.17:** Manually agitating the stacked sieves to induce separation of the soil sample by particle size.



(a) Sieve No. 10 (b) Sieve No. 20

(c) Sieve No. 30 (d) Sieve No. 125

**Figure 6.18:** Retained particle mass on different sieve sizes.

### 6.3.2 Results

After conducting the sieve analysis, the soil sample was classified as well graded sand, accordingly to the Unified Soil Classification System (USCS, see Appendix A), which describes the texture and grade of soil with respect to results of sieve analysis. First of all, more than 50% of the material was larger than the No. 200 sieve size, which results in coarse grain soil. Furthermore, over 50% of the coarse fraction passed through the No. 4 sieve, which corresponds to sand. The sample was clean sand because less than 12% of the sample was fines. In summary, this results in well graded sand (SW classification). This result was compared to the rope test, in which a 1-in diameter ball of sand is compacted and then texture is determined by rubbing between the ball between the samples. Sand feels gritty and does not stick together, which was found in the rope test as shown in Figure 6.19.

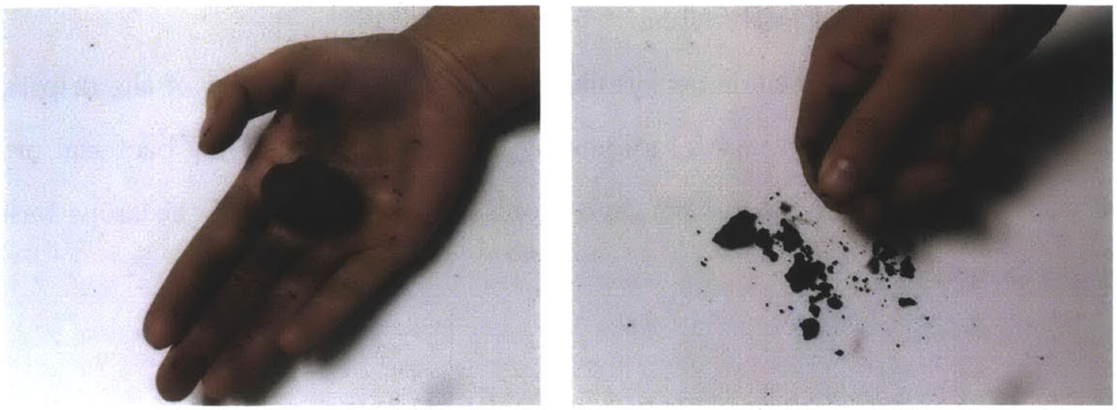
Because soil is different depending on the environment, this method of determining the soil particle composition through the sieve analysis can be applied in the future to different soil samples in order to determine if soil particles will pass through the filters (sieve sizes 42 and 120). In this soil collected in Cambridge, MA, 0.57% of the sample passed through the Chapin filter, whereas the IDE filter did not have any measured soil particles pass through. A summary of the soil particle size breakdown in displayed in Table 6.2. In summary, 99.23% of the soil did not pass through the filter, but overtime, given that neither of the filters can prevent all soil particle sizes passing through, there will be build up that eventually may hinder the emitter performance.

| Sieve Number | Mass of particles (g) | Percent of total mass of soil sample (%) |
|---|---|---|
| 10 | 6 | 22.9 |
| 20 | 18 | 68.7 |
| 30 | 2 | 7.63 |
| 42 | 0.05 | 0.20 |
| 45 | 0.05 | 0.19 |
| 120 | 0.1 | 0.38 |

**Table 6.2:** Break-down of particle size in soil sample

# 7 Conclusion

In order to evaluate the Chapin Bucket Kit and IDE drip kit, both qualitative user testing in rural Nicaragua and quantitative laboratory testing for performance, material properties, and filter clogging were conducted. A focus group of 16 study participants installed both systems on communal land in rural Nicaragua in January 2011 and discovered several design weaknesses in both systems, including that the IDE drip tape was prone to accidental



**(a)** Compacting soil into a 1-inch diameter ball **(b)** Using texture to determine soil type

**Figure 6.19:** Determining soil type through soil texture with the rope test

punctures and the Chapin system was overall difficult to install because of many system components. Overall, users preferred the IDE drip kit for its suitable size for smallholder farming, ease of installation, and low cost. In laboratory testing, the emitter discharge performance for IDE drip kit was determined to be 55.6% in uniformity and 66.8% for the Chapin Super Bucket Kit. It was determined from puncture and tensile tests that were conducted that the maximum pull force and maximum puncture force required to deform the Chapin drip tape was 350 N (467% of maximum human pull force, 100% of the maximum human puncture force) and for the IDE drip tape 75 N (32.5% of maximum human pull force, 53.3% of the maximum human puncture force). The Chapin Bucket Kit filter's hole size was determined to be 0.35 mm (sieve number 20) and the IDE drip kit filter's hole size was 0.125 mm (sieve number 120). Sieve analysis was conducted in order to determine the amount of particle size in a collected soil sample (from Cambridge, Massachusetts) that would pass through the filters. 0.57% of the sample passed through the Chapin filter, whereas the IDE filter did not have any measured soil particles pass through.

User testing overall indicated preference for the IDE kit because of ease of installation, low cost, and suitable size for the average household plot. Laboratory performance testing in general indicates that the Chapin kit had more uniformity in emitter flow and stronger material properties. Ultimately, it is up to users to decide what are the trade-offs that can be made when choosing a PDIK system.

Future work would include performing an accelerated aging test of the drip tape to determine the lifetime of the plastic, measuring the organic matter like bacterial or algae growth that could clog up the system, and monitoring the growth of the crops based on emitter performance.

# Appendices

## A Unified Soil Classification System (USCS)

Virginia Department of Transportation VDOT

**UNIFIED SOIL CLASSIFICATION SYSTEM**

**UNIFIED SOIL CLASSIFICATION AND SYMBOL CHART**

| | | | |
|---|---|---|---|
| COARSE-GRAINED SOILS (more than 50% of material is larger than No. 200 sieve size.) | | | |
| **GRAVELS** More than 50% of coarse fraction larger than No. 4 sieve size | Clean Gravels (Less than 5% fines) | | |
| | | GW | Well-graded gravels, gravel-sand mixtures, little or no fines |
| | | GP | Poorly-graded gravels, gravel-sand mixtures, little or no fines |
| | Gravels with fines (More than 12% fines) | | |
| | | GM | Silty gravels, gravel-sand-silt mixtures |
| | | GC | Clayey gravels, gravel-sand-clay mixtures |
| **SANDS** 50% or more of coarse fraction smaller than No. 4 sieve size | Clean Sands (Less than 5% fines) | | |
| | | SW | Well-graded sands, gravelly sands, little or no fines |
| | | SP | Poorly graded sands, gravelly sands, little or no fines |
| | Sands with fines (More than 12% fines) | | |
| | | SM | Silty sands, sand-silt mixtures |
| | | SC | Clayey sands, sand-clay mixtures |
| FINE-GRAINED SOILS (50% or more of material is smaller than No. 200 sieve size.) | | | |
| **SILTS AND CLAYS** Liquid limit less than 50% | | ML | Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity |
| | | CL | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays |
| | | OL | Organic silts and organic silty clays of low plasticity |
| **SILTS AND CLAYS** Liquid limit 50% or greater | | MH | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts |
| | | CH | Inorganic clays of high plasticity, fat clays |
| | | OH | Organic clays of medium to high plasticity, organic silts |
| **HIGHLY ORGANIC SOILS** | | PT | Peat and other highly organic soils |

**LABORATORY CLASSIFICATION CRITERIA**

| | | |
|---|---|---|
| GW | $C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3 | |
| GP | Not meeting all gradation requirements for GW | |
| GM | Atterberg limits below "A" line or P.I. less than 4 | Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols |
| GC | Atterberg limits above "A" line with P.I. greater than 7 | |
| SW | $C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3 | |
| SP | Not meeting all gradation requirements for GW | |
| SM | Atterberg limits below "A" line or P.I. less than 4 | Limits plotting in shaded zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols. |
| SC | Atterberg limits above "A" line with P.I. greater than 7 | |

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:

Less than 5 percent ........ GW, GP, SW, SP
More than 12 percent ........ GM, GC, SM, SC
5 to 12 percent ........ Borderline cases requiring dual symbols

**PLASTICITY CHART**

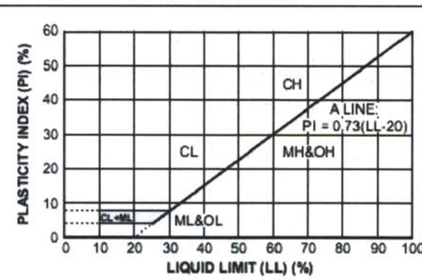



**Figure A.1:** The Unified Soil Classification System (USCS) relates soil type to sieve number

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