

Comparison Of Subsurface And Surface Drip Irrigation Systems Using Responsive Sensor Control In A Controlled Indoor Environment In Ontario

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Abstract Throughout history, humans have depended largely on agricultural products for basic survival. As technology continues to develop, new ways of more efficiently cultivating these crops have emerged. People have tried various different techniques: using better soil, changing irrigation schedules and methods, and seed improvements to list a few, in hopes of improving yield. This study explores the effectiveness of subsurface irrigation compared to traditional surface drip irrigation in water conservation whilst maintaining healthy crop growth. Using baby heirloom lettuce as the test plant, both irrigation systems were designed and monitored under controlled indoor conditions, with soil moisture sensors changing irrigation schedule based on readings. By doing so, the study aims at determining how subsurface irrigation and responsive sensor control can improve irrigation efficiency. This offers insights into sustainable, data-driven farming practices, allowing plant growers around the world to have a more optimized and efficient system. The results showed that subsurface irrigation is better for plant growth compared to above surface drip, but uses slightly more water.

Keywords — Agriculture, irrigation efficiency, lettuce, moisture sensors, subsurface irrigation.

I. INTRODUCTION

Agriculture remains one of the most essential and water-intensive human activities, making up nearly 70% of all freshwater usage. By 2050, with the world population expected to be at 9 billion people, agricultural demands are expected to increase by 50% and a 15% further water usage, highlighting the potential pressures on limited water resources [4]. In response to the oncoming challenges, researchers and farmers alike have been searching for new, efficient, irrigation strategies that reduce water consumption whilst balancing results. Therefore, efficient water management and usage has been a hot topic when it comes to discussions about ensuring future food safety and sustainability.

Traditional irrigation techniques, including surface drip and sprinkler systems, have improved water distribution and plant uptake compared to older flood-based methods. However, these systems still have shortcomings, the main one being loss of water through evaporation. This is especially prominent in warm or dry environments, where evaporation is sped up. In addition, fixed irrigation schedules often don't account for variations in soil moisture and also plant's specific water needs during a growth period, leading to over or under watering. As a result, over 60% of water used for agriculture is wasted or used inefficiently.

Subsurface irrigation has emerged as a potential solution to these challenges. By delivering water directly to the root zone through underground emitters, subsurface systems reduce evaporation and provide more consistent soil moisture conditions. When combined with soil moisture sensors to automate irrigation schedules, water use can be precisely controlled to match the plant's needs, reducing unnecessary water use and improving water absorption.

In regions such as Southern Ontario, where horticultural crops like tomatoes, peppers, and strawberries dominate production, irrigation efficiency is particularly critical. Bernier et al. [1] found that five of six Ontario farms either over- or under-irrigated relative to crop demand, with subsurface systems performing closest to optimal levels. Likewise, Van Acker [5] reported water-use efficiencies of up to 95% for subsurface drip systems compared with 80–90% for conventional surface methods. These findings highlight both the promise of SDI and the continuing inconsistency in irrigation practices within the region. Studies from other regions around the world have also indicated the water-saving potential of subsurface systems. Studies from semi-arid China indicated that deficit SDI improved water-use efficiency and stabilized yield [7], and research in Japan showed an optimized subsurface system increased soybean and corn yields by up to 50% [6]. However, both of these studies lacked direct growth-rate measurements and were not tested in temperate indoor environments, similar to those in Ontario.

Previous studies have investigated irrigation methods independently, and compared those results to other studies. However, limited research has been done comparing surface and subsurface irrigation systems integrated with soil moisture sensors in identical environments. This study addresses that gap by testing both systems using baby heirloom lettuce as the model crop under controlled indoor conditions.

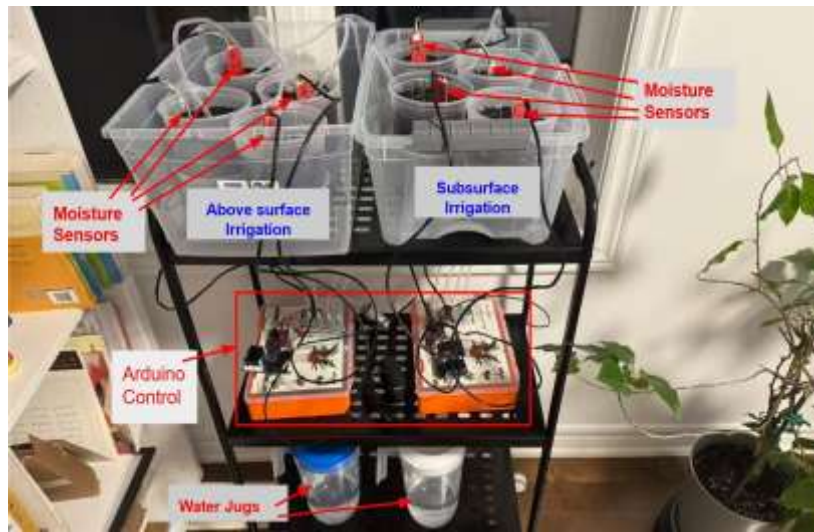
This research aims to find whether subsurface irrigation, when combined with moisture sensor control, can use less water while keeping plants healthy and growing faster than traditional surface drip irrigation. Using the indoor crop baby heirloom lettuce, both irrigation systems were monitored through soil moisture sensors that adjusted watering schedules automatically.

II. MATERIALS AND METHODS

Eight pots of baby heirloom lettuce (*Lactuca Sativa*) were used to compare subsurface irrigation (SSI) and above-surface irrigation (ASI). All pots were of equal size, and contained the same soil mix, seedling age, and similar lighting conditions.

Four pots receive subsurface irrigation (SSI): the water outlet is positioned 6 cm below the soil surface. Four pots receive above-surface irrigation (ASI): water is delivered at the surface. Each pot has a capacitive moisture sensor inserted 5 cm deep; a single uniform moisture threshold is used across all pots so that when a pot's reading drops below the threshold, an automatic pump delivers water to that pot from a dedicated reservoir (one identical jug for SSI, one identical jug for ASI). The pump, moisture sensor, tubing, and Arduino Leonardo comes from the Elecrow Arduino Automatic Smart Plant Watering Kit 2.1 purchased from RobotShop. Holes for subsurface irrigation are drilled using a 79/6 drill bit in 1.5cm intervals. Reservoirs start full and are refilled only when nearly empty. Each reservoir has a lid, ensuring minimal evaporation. All additions are measured with a graduated cup and logged per irrigation method to track cumulative water use. Pots are placed in groups atop a rack on the same level. The setup is shown in Figure 1.0.

Fig. 1.0. Experimental setup showing the subsurface and above-surface irrigation systems for baby heirloom lettuce. This image was taken 3 days after seeding.



During the seed germination stage, each pot is first watered with 400ml of water pre-seeding, and seeds are planted after 1 day. Each pot is planted with 3 seeds to increase chances for at least 1 seed to sprout and grow. Plastic wrap is used to cover each pot to reduce evaporation. When the seeds have sprouted, the plastic wrap would be removed, ensuring proper growth. Plants are monitored daily with photographs to track growth (height/leaf count or image-based canopy area), and sensor readings and pump activations are logged at each watering event. 25 days into the experiment, all plants except the largest based on average leaf size in each pot are removed, ensuring fair nutrient distribution. The experiment runs until harvest (about 5–7 weeks).

The initial soil moisture threshold was set to 20%. Halfway through the second week, the threshold was adjusted to 45% for all pots to better reflect observed plant water uptake patterns. Each activation will turn the pump on for 0.5 seconds. All adjustments were logged and applied equally across both irrigation treatments. Changes should be made based on soil moisture retention and observations.

The primary outcome is water efficiency, calculated as total water applied per pot, comparing SSI vs ASI. Secondary outcomes include growth rate. Data including leaf size, moisture levels, and water usage are tracked and compared.

III. RESULTS

To determine the influence of the irrigation system on plant growth and water consumption, two test groups were grown. The first group had subsurface irrigation, whereas the second had above surface drip irrigation. Each group consisted of 4 different samples. All plants were grown in an identical controlled indoor environment. The size of the leaves and water usage was tracked and compared.

Monitoring of average leaf size of every plant, water consumption, moisture retention, and visual observations were done in intervals of 2-3 days. 40 days into the experiment, not including the water used during seed germination, the subsurface irrigation plants in total used 860mL of water, whereas the above surface drip irrigation plants in total used 770mL of water. The average leaf size of subsurface irrigated plants are visibly larger than above surface drip irrigated plants. Below are figures illustrating both average leaf size and the size of the largest leaf over the 40 day time period. Measurements tracked the

length of the leaf stem. Subsurface Irrigation (SSI) is denoted by blue lines and labeled as S0–S3, while Above-Surface Irrigation (ASI) is represented by red lines labeled A0–A3.

Fig. 2.0. The size of the biggest leaf in each pot over the 40 day period. It starts on day 15 when the leaves are measurable.

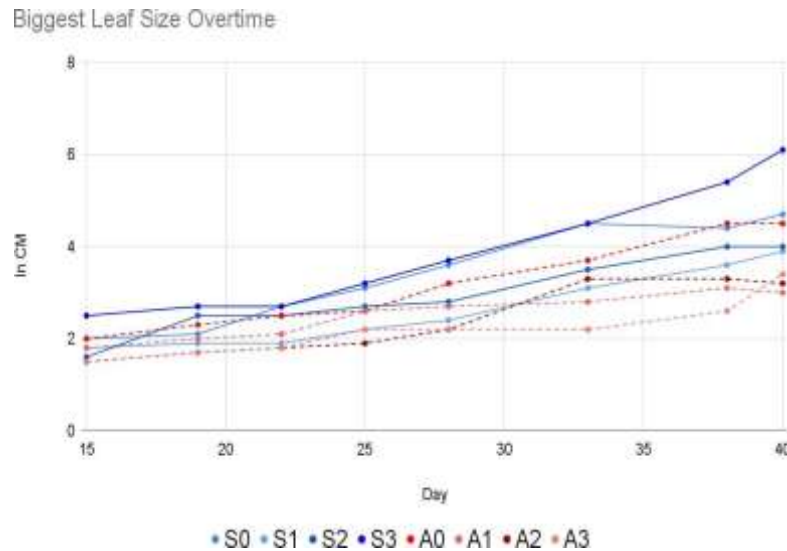
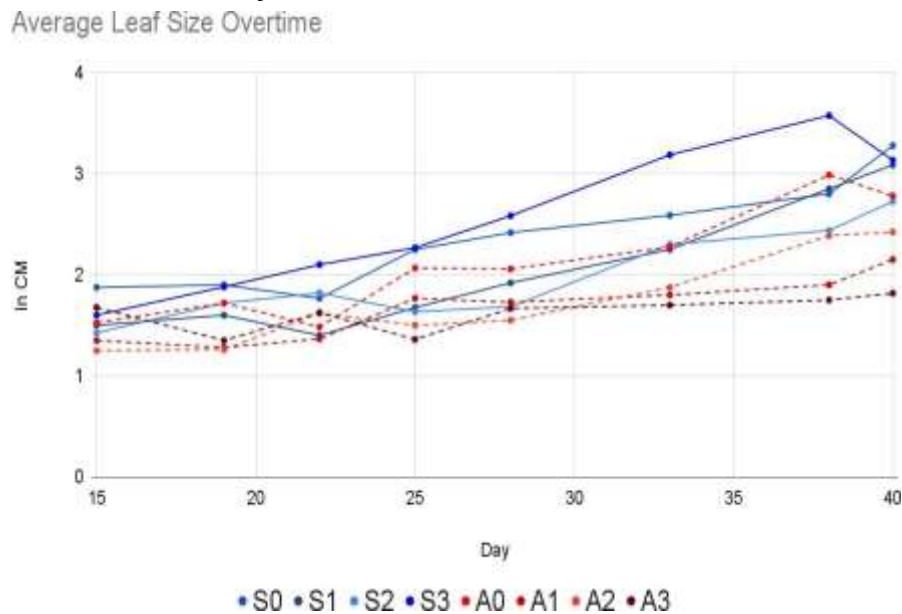


Fig. 3.0. The average size of the leaves in each pot over the 40 day period. It starts on day 15 when the leaves are measurable.



The graphs below show moisture sensor readings over time in both groups, we can see that the subsurface irrigated plants are more volatile compared to the above surface drip irrigated plants. The spike at the beginning was due to the seeding phase requiring large amounts of water. At around the 100th interval, sensors were recalibrated, resulting in a drop across all sensor readings. Any other outliers and spikes are caused by sensor reading errors. An example would be ASI3 dropping to 0 at the 240 interval.

Fig. 4.0. The readings of each individual subsurface irrigation sample over the 40 day period. X-axis shows sampling interval, Y-axis represents moisture percentage.

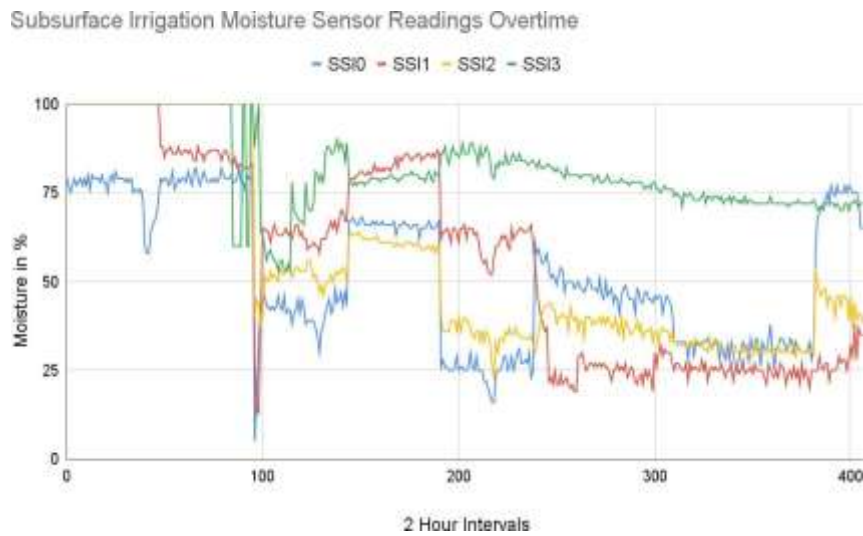
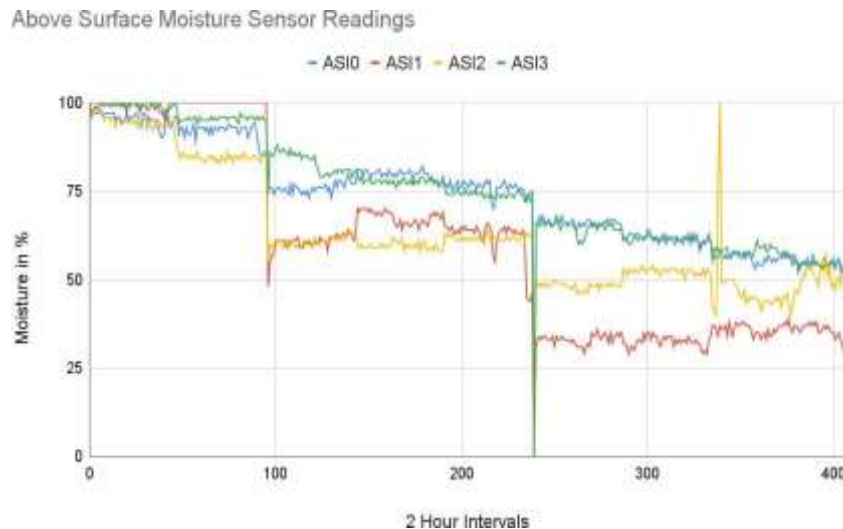


Fig. 5.0. The readings of each individual above surface drip irrigation sample over the 40 day period. X-axis shows sampling interval, Y-axis represents moisture percentage.



IV. DISCUSSION

The results demonstrate a clear difference in growth patterns between Sub-Surface Irrigation (SSI) and above-surface irrigation (ASI) when both soil moistures are controlled via identical sensor control loops. Although previous research mentions water-saving patterns for subsurface irrigation, the results here show something else. In this study, SSI overall grew larger leaves and showed faster growth compared to ASI, suggesting that delivering water directly to the root zone provides an advantage for lettuce plants. This observation is consistent with findings from subsurface systems in Ontario and internationally, where SDI and optimized SIS systems have been shown to increase yields or improve crop performance [2], [5], [6]. However, the trade-off is an increased water consumption.

These results indicate that while subsurface irrigation promotes accelerated growth, it

may not necessarily reduce total water consumption in low-evaporation indoor environments. Similar patterns have been noted in previous Ontario trials where unusually wet conditions masked the water-saving benefits of SDI, showing that environmental context greatly influences irrigation efficiency [2]. Instead, the increased water use in the SSI group likely reflects the fact that in a low-evaporation indoor environment, the evaporation-reduction benefit of SSI is negated, and the stimulated plant growth benefit takes over, resulting in higher transpiration. This aligns with studies showing that SDI can improve crop vigor even when efficiency gains are not always reflected in total applied water [5], [7].

A notable difference between the two irrigation systems was the behavior of the moisture sensors over time. The SSI pots showed sharper fluctuations in moisture readings, whereas the ASI pots produced smoother, more gradual changes. Although this initially appeared counterintuitive, the pattern can be explained by the physical placement of the sensor relative to the water source. Because the subsurface emitters were positioned adjacent to the sensors, each irrigation event caused a brief spike in detected moisture before the water dispersed throughout the surrounding soil. In contrast, the ASI pots received water at the soil surface, allowing moisture to diffuse downward slowly and evenly, resulting in less pronounced changes in the sensor output.

This distinction highlights an important consideration for automated irrigation systems: sensor depth and proximity to emitters can influence activation frequency, potentially leading to higher watering rates even when the root zone is adequately hydrated. Similar advantages of smart, sensor-driven irrigation over time-based scheduling have been shown in controlled SIS systems, where moisture-sensor feedback produced more stable and efficient watering patterns than fixed scheduling alone [8]. Thus, part of the increased water use in the SSI group likely reflects the sensor's increased sensitivity to localized wetting rather than true differences in soil moisture availability.

Compared to previous studies in Southern Ontario, these results both align with and expand upon earlier findings. Bernier et al. [1] showed that subsurface irrigation came closest to meeting optimal crop water demand among six Ontario farms, but their study lacked direct growth-rate measurements—an area this experiment contributes to by tracking leaf size over time. Economic studies also highlight that SDI's long-term viability depends on improved yield or plant performance [3], which supports the relevance of documenting faster growth in SSI plants as seen here. Together, these comparisons suggest that although the water-saving benefits of SDI are not universal across environments, the growth advantages observed in this study are consistent with the broader literature and may hold practical value in precision agriculture applications.

A. Limitations

Despite clear trends in the observed data, several limitations should be acknowledged with regards to experiment design when interpreting the results. Firstly, as the sensor was placed near the subsurface emitters, the close proximity resulted in faster moisture readings and spikes. In comparison, the ASI sensors placed in the same positions received water more gradually. This could've potentially affected irrigation activation and frequency. A second limitation is the relatively small sample size. Though 4 samples per group eliminates most seed-related variances, it could still limit the results generalization. Additionally, growth metrics were mainly on leaf size, not total biomass or root development, which could underestimate the differences between SSI and ASI. Furthermore, the controlled indoor environment doesn't represent a real world agricultural scenario accurately. Evaporation was significantly reduced due to calmer climates, thus potentially not showing the full benefits of SSI—an issue also noted in real Ontario trials conducted under unusually wet field conditions [2]. This goes to say that

the time of year the experiment was conducted also matters. As this was conducted in late fall and early winter, the drier environment and reduced sunshine would negatively affect plant growth. Lastly, the moisture sensor thresholds were the same throughout samples for both SSI and ASI, even though the optimal moisture level could vary for individual plants and different irrigation methods.

V. CONCLUSION

With increasing agricultural demand, finding a new way of irrigating almost seems like a must. This experiment set out to determine whether subsurface irrigation (SSI), when controlled by moisture sensors, could use less water while sustaining healthy plant growth compared to above-surface irrigation (ASI). The results showed that although SSI plants grew faster and developed larger leaves, they also used slightly more water overall. This increased water use likely reflects higher demand from larger plants rather than inefficiency in the system. Moisture-sensor trends revealed that SSI pots experienced sharper fluctuations due to the proximity between sensors and subsurface emitters, which may have triggered more frequent irrigation events. In contrast, ASI pots showed smoother moisture changes. These findings suggest that sensor placement and calibration play an important role in automated irrigation performance. Compared with previous research, which often reports strong water- saving benefits for subsurface systems in outdoor or high-evaporation settings, this study shows that in low-evaporation indoor environments the main advantage of SSI may instead be improved growth rather than reduced water use. Overall, this experiment demonstrates that subsurface irrigation can promote stronger lettuce growth under controlled conditions, but its water-saving potential depends heavily on environmental factors and sensor configuration. Future work with refined sensor placement, varied thresholds, and expanded trials would help clarify how to optimize both systems for efficiency and consistency.

ACKNOWLEDGMENT

I give special thanks to Dr. George Anwar for guiding me throughout the research and paper writing process. I also thank the Cambridge Center of International Research for giving me this opportunity and their support in editing and journal searching.

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