Fabrication of a Biodegradable, Nutrient-Rich, Orange Peel-Loaded Hydrogel for Thermally-Programmed Release of Water to Maintain Soil Moisture

Introduction

According to the WSIag, close to 40% of global croplands have experienced water scarcity in the past and this number will continue to increase in the future. Additionally, climate change intensifies droughts around the world, causing more alarming and severe circumstances. If we continue on this path, there will not be enough freshwater to match the water needs of the crops necessary for the growing population. The need for new ways of conserving and optimizing water is crucial, especially now. One promising solution is to preserve water directly in the soil and prevent rapid dehydration. This allows farmers to take full advantage of the water they put in soil and provides a way to combat the dehydration caused by the heat of some arid climates. For example, corn crops need to have a SMP value of 50-80 kilopascals to grow. So, in areas with intense sunlight, less rainfall, and higher temperatures, farmers have to constantly water the corn. This can be hard to maintain in areas with water scarcity. In addition, this regimen will be very expensive because of electricity and water consumption costs. This is also the case for many other crops. A mechanism by which the soil can retain moisture, to minimize water requirements for the crops grown in that soil, is desperately needed and is the focus of the research presented herein. Hydrogels have been shown to retain, and then release water, in response to external changes in temperature, and may prove useful as a biodegradable and environmentally-friendly soil additive. Also, orange peels are extremely efficient at absorbing and releasing water. According to work by Parashar, et al., the reason orange peels can retain so much water is due to their high number of natural water-absorbent polymers. Additionally, if used as a soil additive, orange peels would naturally compost into the soil, and provide organic matter, making the soil rich in nutrients and improving soil structure.

Engineering Goal/Purpose

The engineering goal of this research is to design and develop a thermo-responsive hydrogel embedded with orange peels, that will preserve soil moisture and increase water retention. The specific thermo-responsive hydrogel to be used is composed of methylcellulose (MC), which is stable at a typical crop-soil pH range from 6 to 7, and has a gelation temperature of ~65°C. As such, the MC hydrogel will hold water when the soil is cool and moist, but swell and release water as the soil dries with external heating, and the surface-soil temperature rises from normal 35°C to near 65°C. To maximize the water-load of the hydrogel, crushed orange peel powder will be integrated into the MC-hydrogel, to provide a new, unique, and drought-condition responsive soil water release mechanism, to lessen watering requirements, minimize drought conditions, and thereby increase crop growth.

I. Natural Dehydration of Multiple Peels

In order to assess which fruit peel would retain moisture most effectively, 5 pots, each containing 3 cups of soil and 1 cup of different fruit peels, such as lemon, orange, apple, banana, and mango, were placed under two heat lamps. These 5 fruits were chosen due to their water-enhancing structural properties and their availability as natural, household waste products. Additionally, 1 control pot, containing 3 cups of soil with no additives was placed for comparison. In all 6 pots, no additional water was added (Fig. 1A).

Fig. 1A: The set-up of the 6 pots under heat lamps on Day 1. (Image taken by the student, 2025)

Using a Digital Soil Moisture Meter, the VWC of each pot was measured until all the pots reached 0%. This took 13 days. Results (indicated by Fig. 1B and Fig. 1C) showed the three best performing peels were the orange, banana, and apple peels.

Day	Control	Lemon	Orange	Banana	Apple	Mango
1	51.0%	52.0%	52.0%	52.0%	50.0%	49.0%
2	25.0%	48.0%	52.0%	50.0%	50.0%	26.0%
3	16.0%	40.0%	51.0%	48.0%	36.0%	24.0%
4	14.0%	28.0%	47.0%	42.0%	29.0%	20.0%
5	9.0%	22.0%	41.0%	37.0%	21.0%	18.0%
6	8.0%	10.0%	32.0%	27.0%	14.0%	14.0%
7	6.0%	9.0%	25.0%	19.0%	10.0%	12.0%
8	6.0%	6.0%	16.0%	6.0%	10.0%	6.0%
9	4.0%	6.0%	8.0%	6.0%	10.0%	6.0%
10	4.0%	2.0%	7.0%	2.0%	6.0%	6.0%
11	2.0%	2.0%	7.0%	1.0%	6.0%	0.0%
12	0.0%	0.0%	0.0%	1.0%	2.0%	0.0%
13	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Fig. 1B: % Moisture for Soil with Added Fruit Peels (prepared by the student in Excel, 2025)

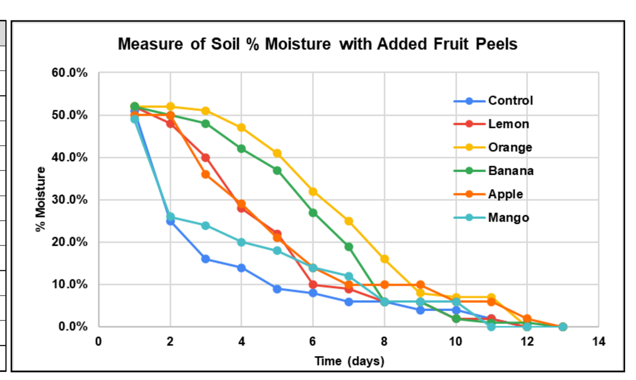


Fig. 1C: A Graphical Depiction of % Moisture Loss over 13 days (prepared by the student in Excel, 2025)

II. Comparative Analysis of Fruit Peels' Water Retention Capacity

To further evaluate which fruit peel would be the optimal choice to include in the hydrogel, orange, apple, and banana peels were dried in their natural state and powder form. To reach the powdered state, the peels were crushed in a coffee grinder. For the drying process, the peels/powders were placed in a drying oven at 50°C for 7 days. The mass of each peel and powder was taken before and after being dried (Fig. 1B) in order to calculate the amount of water mass lost. By dividing the water mass lost by the original mass, the percent of water in the original peels was calculated. The orange peels showed the highest capacity for water and the greatest %-water content out of the three peels.

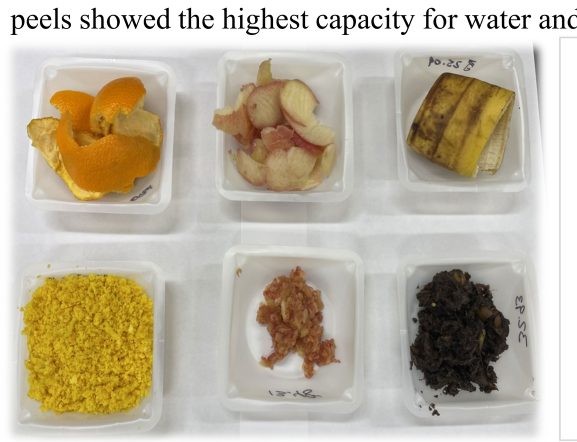


Fig. 2A: Orange, apple, and banana peels before drying process (Images taken by the student, 2025)

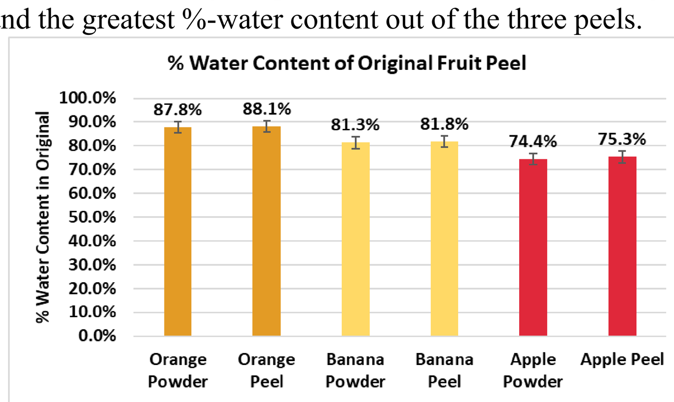


Fig. 2B: A comparative bar graph depicting the percentage of water content of each original fruit peel (Graph prepared by the student in Excel, 2025)

Fruit Type	Original Mass	Dried Mass	Water Mass Lost	% Water in Original Peel	Average % Water In Fruit
Orange Powder	32.93	4.01	28.92	87.8%	
Orange Peel	25.07	2.98	22.09	88.1%	88.0%
Banana Powder	13.48	2.52	10.96	81.3%	
Banana Peel	23.01	4.19	18.82	81.8%	81.5%
Apple Powder	36.42	9.33	27.09	74.4%	
Apple Peel	32.85	8.11	24.74	75.3%	74.8%

Figure 2C: A table exhibiting the mass of the various peels/powders before and after drying and the water mass. (Table prepared by the student in Excel, 2025)

III. Characterization of Orange Peel and Banana Peel Morphology and Content via Scanning Electron Microscopy, EDS, and ATR-FTIR Spectroscopies

Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were used to analyze the dried banana peels and the dried orange peels. The SEM of Figure 3A highlights the porous structure of the orange peels which would prove advantageous in absorbing and retaining water. Furthermore, the EDS of the dried orange peels (Fig. 3B) highlights carbon as the most abundant element, however, it also shows the presence of measurable amounts of beneficial nutrients (for the soil), such as magnesium, potassium, calcium, and phosphorus. The ATR-FTIR spectrum of the orange peel, wet versus dried, further highlights the ability of the crushed biomaterial at retaining water, due to the presence of an O-H spectral peak at 3400 cm^{-1} in the wet spectrum. Conversely, the SEM for the banana peels (Fig. 3D) demonstrates that there are fewer visible pores, indicating a lower potential for water retention. Similarly, the banana peel EDS shows the presence of carbon, as well as possible soil nutrients, with the most notable being potassium. Like orange peels, the banana peel ATR-FTIR spectrum highlights a high-water capacity of the material at 3400 cm^{-1}.

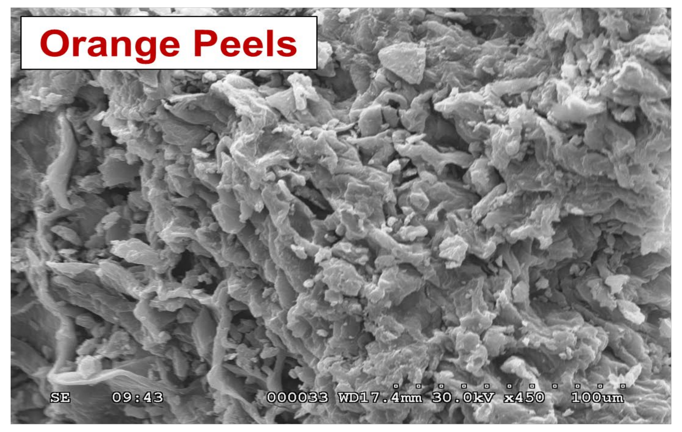


Fig. 3A. SEM image of orange peel

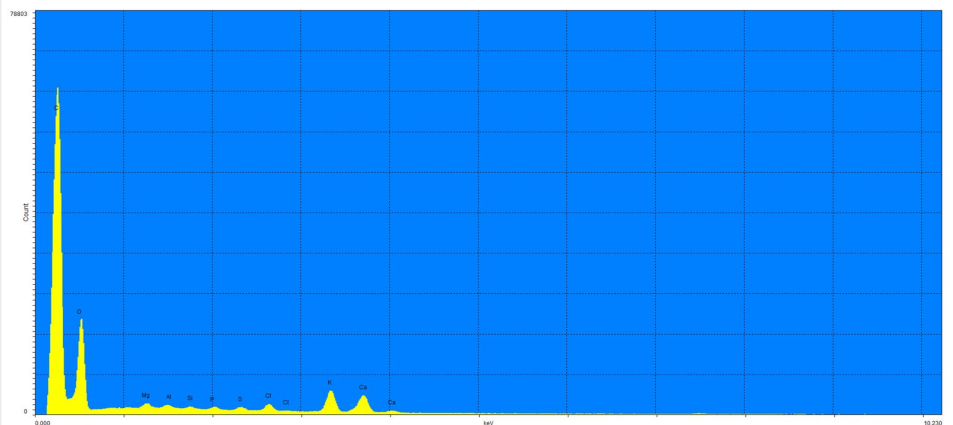


Fig. 3B. EDS image of an orange peel indicating useful and favorable nutrients

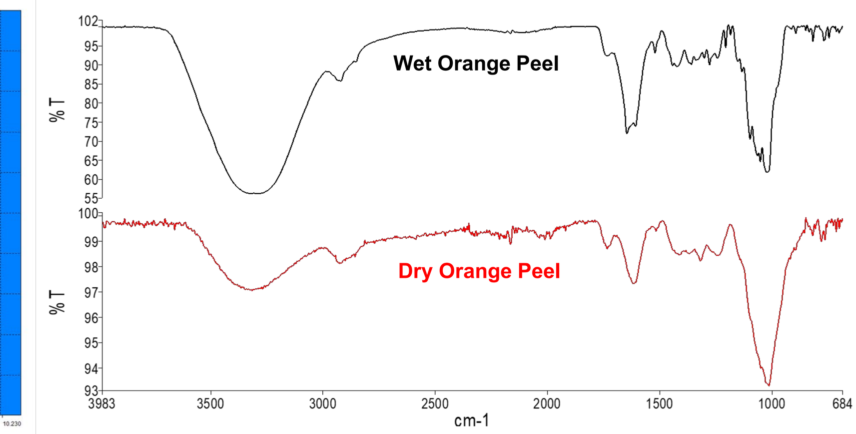


Fig. 3C. FTIR Image of wet (top) and dry (bottom) orange peels before and after being loaded with water

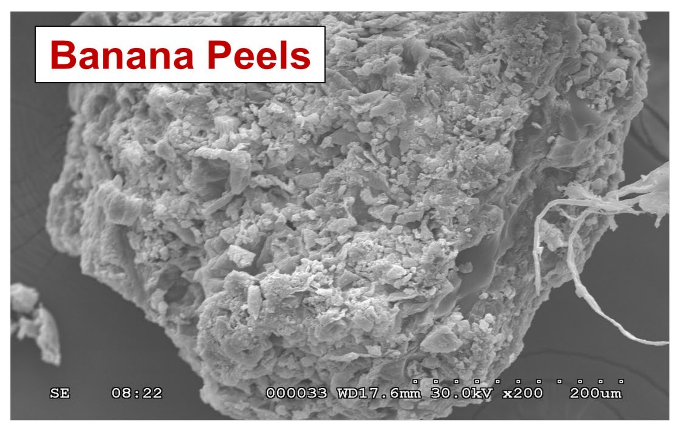


Fig. 3D. SEM image of banana peel

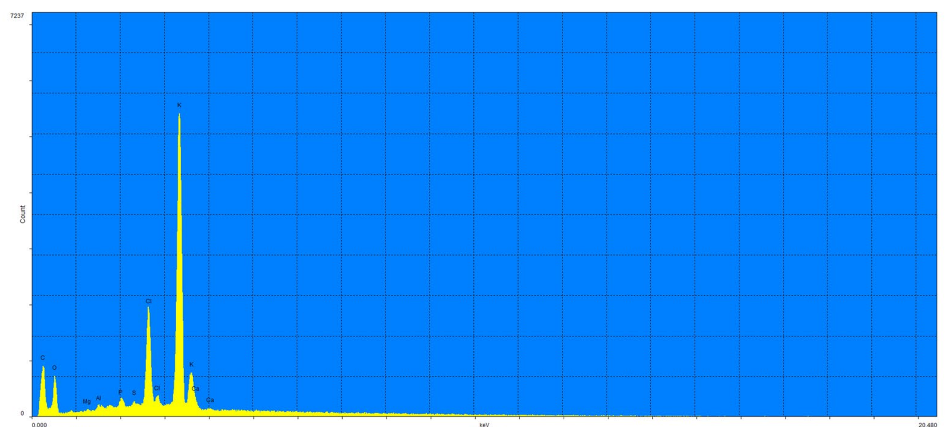


Fig. 3E. EDS image of a banana peel

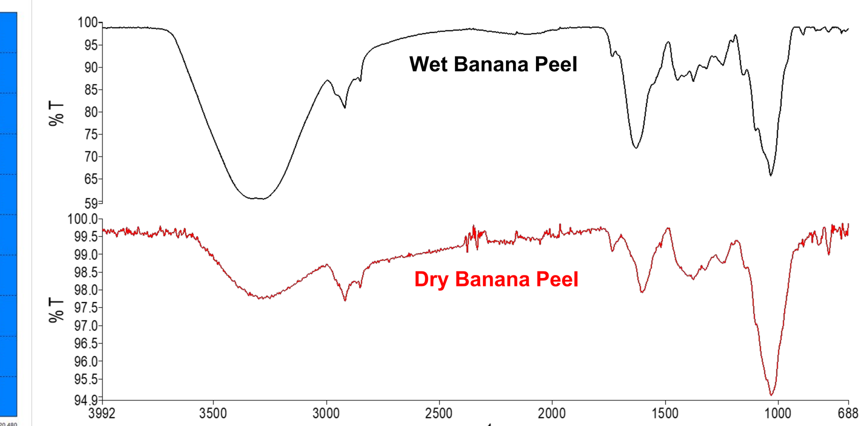


Fig. 3F. FTIR Image of wet (top) and dry (bottom) banana peels before and after being loaded with water

Fig. 3 SEM images and EDS spectra were taken by the student on a Hitachi S-3500N in 2025; ATR-FTIR spectra were collected by the student on a PE Spectrum 100 in 2025.

IV. Purposeful Loading of Water in Dried Orange Peels and Dried Banana Peels to Find Best Water Absorption Capacity

In order to decide which peel retains moisture most effectively and would prove most beneficial in the hydrogel, the water absorption capacity of both the orange peel and the banana peel was tested. After crushing and drying each peel, the powders were measured for their mass and then put in an 86% RH chamber for 1 week (Fig. 4). To calculate the percent of water mass gained by each peel, the water mass added was divided by the original mass of the powder and then multiplied by 100 (Table 1). Results indicated by Figure 5 show that the orange peel powder performed better than the banana peel powder and can absorb almost 2 times its weight in water. Ultimately, the orange peels are the best fit for the hydrogel due to their outstanding water absorption capabilities, porous structure, nutrients, and water mass capacity.

Fig. 4: Schematic of the drying of orange and banana peels, followed by purposeful rehydration at 86% Relative Humidity, to determine maximum water absorption of each. (Diagram created by the student with BioRender, 2025)

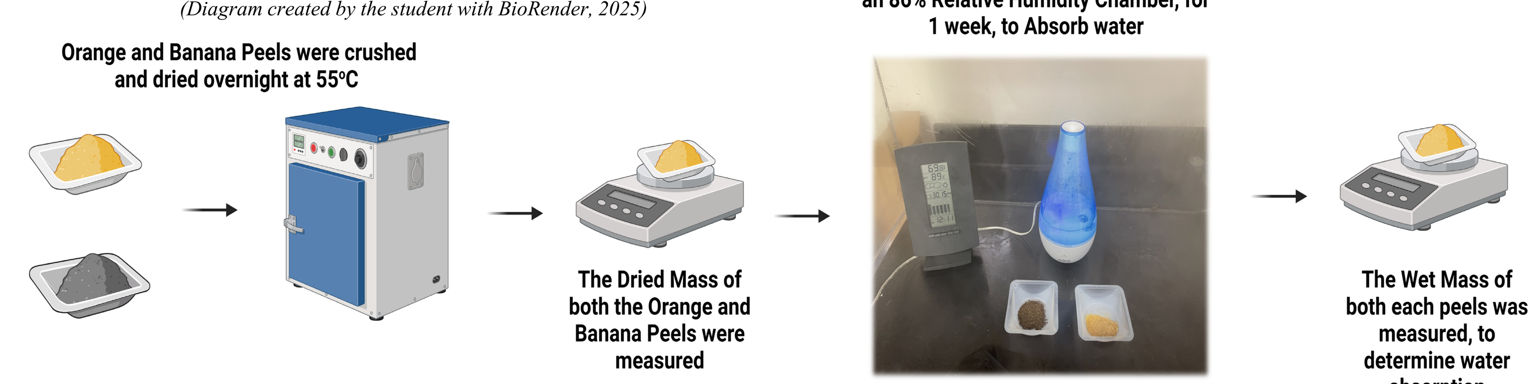
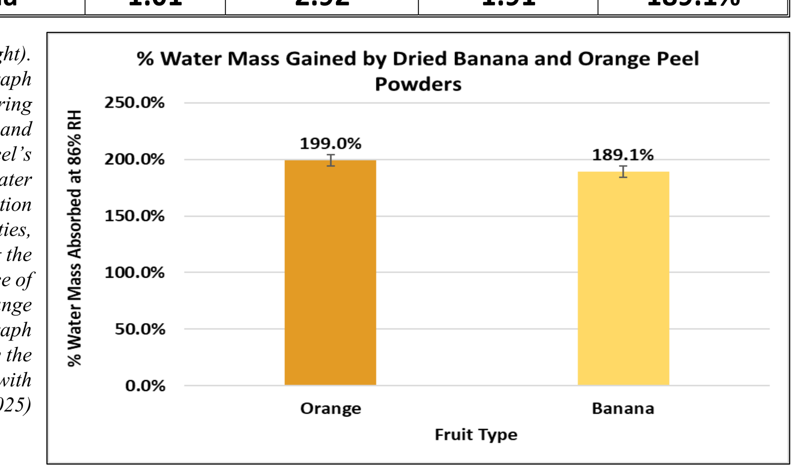


Table 1. Rehydration Results (prepared by the student in Excel, 2025)

Fruit Type	Oven Dried Mass	Wet Mass after 86% RH	Water Mass Gained	% Water Mass Gained
Orange	1.01	3.02	2.01	199.0%
Banana	1.01	2.92	1.91	189.1%

Figure 5 (right). A graph comparing orange peel and banana peel's water absorption capabilities, highlighting the performance of the orange peels. (Graph prepared by the student with Excel, 2025)



V. Fabrication of a Methyl Cellulose Hydrogel Integrated With Orange Peels

The methyl cellulose hydrogel was chosen due to many reasons. The hydrogel's thermoresponsivity makes it particularly useful because it only disperses water when necessary. Since the hydrogel has a large water-holding capacity, it can dissipate water over a longer period of time. This all increases the conservation of water in agriculture. Due to the hydrogel's biodegradability, it will not cause harm to its environment either. Once this solution is integrated with the orange peels, its benefits are significantly improved. This solution can then be dried to create a water-retaining substance for soil. Figure 5. below highlights the method used to produce the Orange Peel – Hydrogel (OP-HG). A plain Hydrogel (without inclusion of orange peels, was also created, for control experiments to come.

Figure 6. Creation of the Orange Peel Hydrogel (OP-HG)

(Fig. 6 diagram created by student with BioRender, 2025)

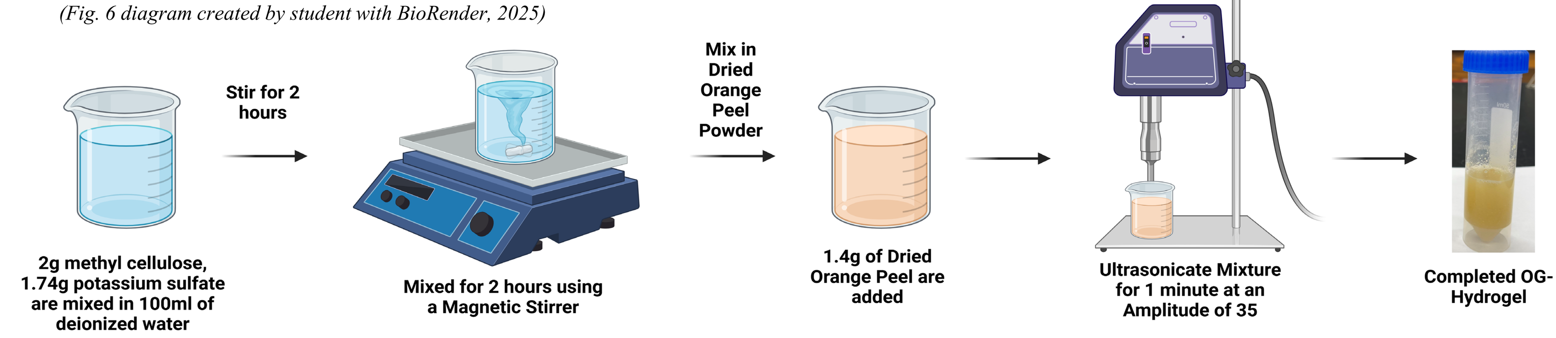
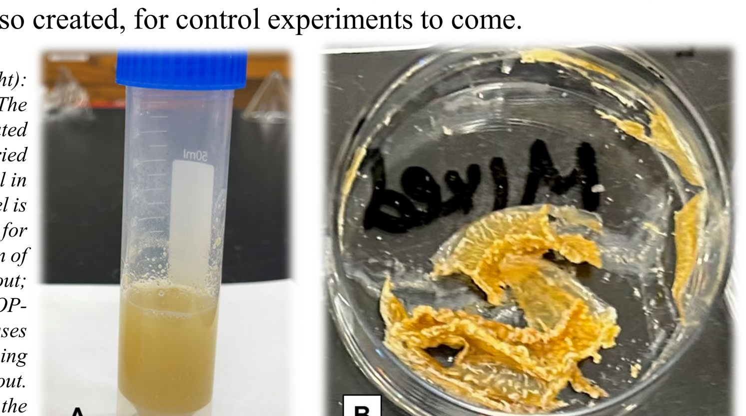


Fig. 7a-b (right): (a) The ultrasonicated mixture of dried orange peel in liquified hydrogel is homogeneous, for uniform inclusion of the OP throughout; (b): the dried OP-Hg possesses water-absorbing OP throughout. Images taken by the student, 2025)



SEM and ATR-FTIR evaluation of the control, plain Methyl Cellulose Hydrogel and the Orange-Peel-Infused Hydrogel (Figs. 8-10) highlight successful uniform inclusion of the natural water absorbent material throughout the hydrogel composition.

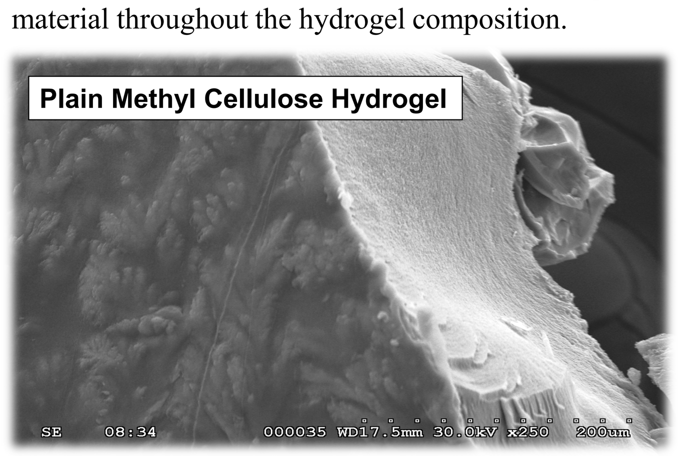


Figure 8 (left): The 30kV, 250X SEM image of the plain, dried hydrogel, without OP, demonstrates a smooth, homogenous consistency throughout. (Image taken by student on Hitachi S-3500N, 2025)

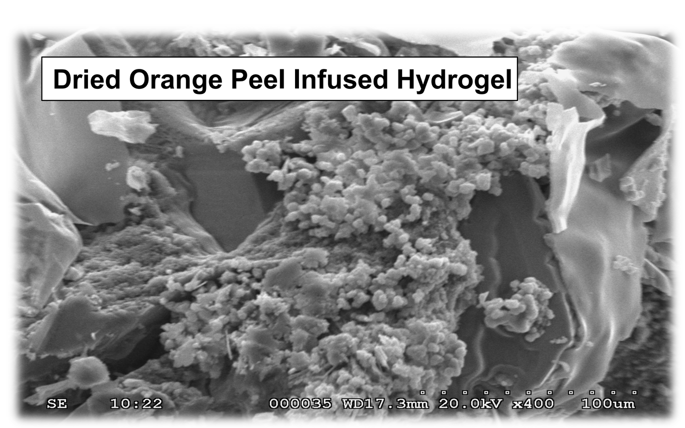


Figure 9. (left): The 20kV, 400X SEM image of the orange peel infused Hydrogel (OP-HG) provides evidence for uniform distribution of the OP water absorbent. (Image taken by student on Hitachi S-3500N, 2025)

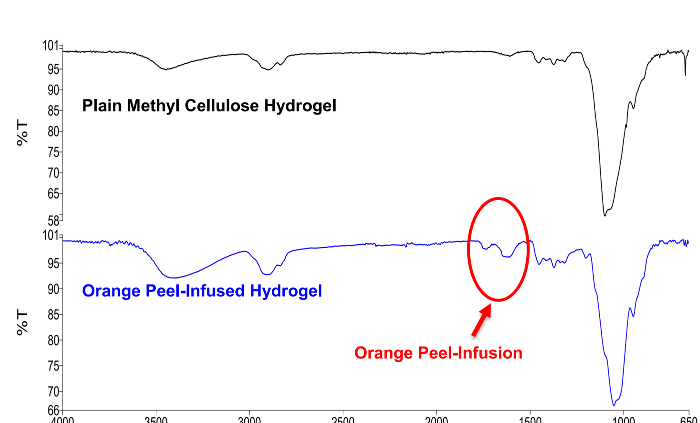


Figure 10. Comparison of the ATR-FTIR spectrum of the methyl cellulose hydrogel with that of the Orange Peel-Infused Hydrogel provides further evidence for successful inclusion of the natural water absorbent. (Spectra collected by student on a PE Spectrum 100, 2025)

VI. Improved Water Retention in Soil with the Orange Peel Hydrogel

To evaluate the timed release of water from the OP-HG, to promote the prolonged moisture of soil in arid conditions, 4 configurations of soil testing were constructed. Four pots, each with 150ml of soil, were separately arranged with 1g of infused additive; 1g of OP-HG, 1g of OP, 1g of Hg, and no additive (as the control). Using a coffee grinder, the additives were blended in the soil. Approximately 23ml of water was added to each, to bring the % moisture of each to 15.5%. All four pots were placed in the horticulture lab window, with direct daytime sunlight (Fig. 11).

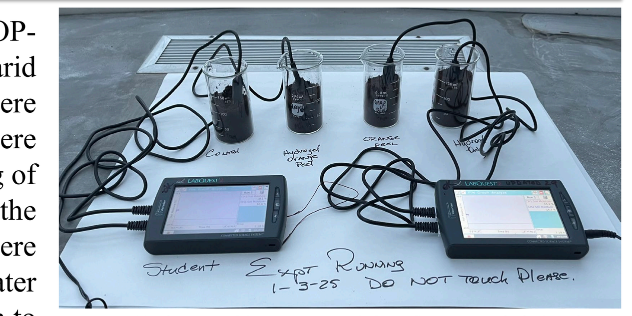
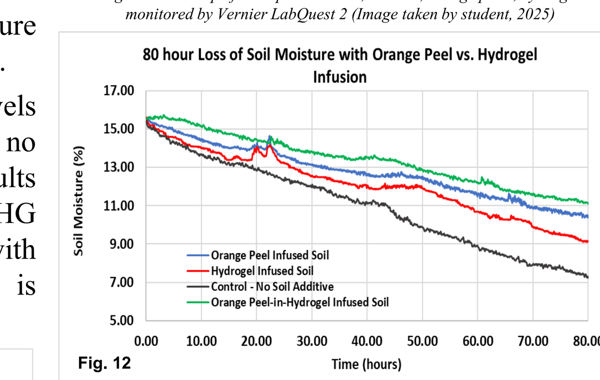
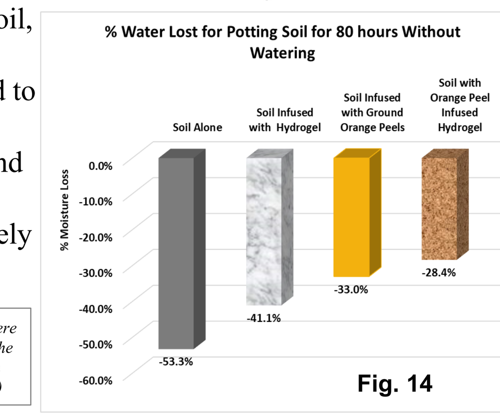
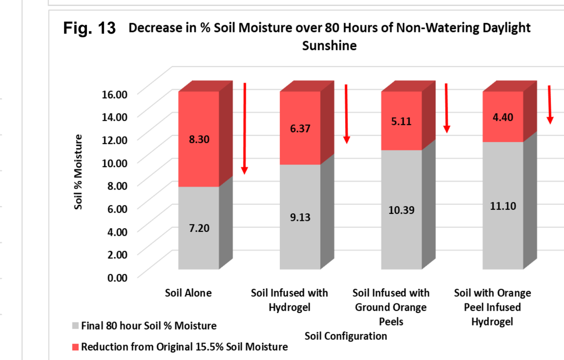


Fig. 11. The setup of the 4 pots- control, OP-HG, orange peels, hydrogel monitored by Vernier LabQuest 2 (Image taken by student, 2025)

Using a Vernier LabQuest 2, the %-Moisture levels of each pot's soil was recorded for 80 hours, with no additional water added for the duration. Results highlighted in Fig. 12 indicate that the OP-HG performed the best out of all 4 samples, with reduction of %-Moisture only to 11.10%. This is compared to the OP-infused, Hg-infused, and control-soil, which decreased to 10.39%, 9.13%, and 7.20%, respectively (Fig. 13).







Figs. 12-14 were prepared by the student with Excel, 2025)

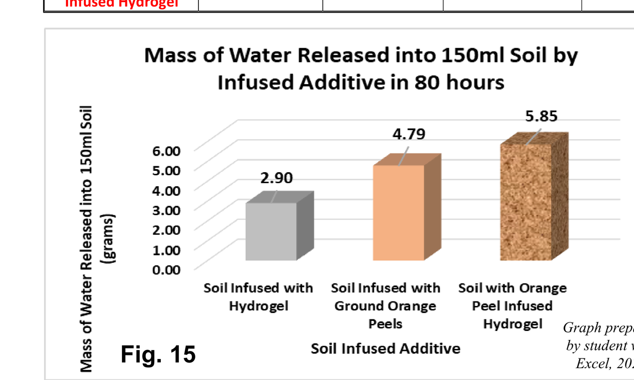
Considering the amount of water lost for each soil configuration (i.e. OP-HG lost 4.4% from the original 15.5%), Fig. 14 highlights that normal, control soil lost 53.3% of its moisture, while OP-HG outperformed all other infusion materials, losing only 28.4% of its moisture over the 80-hour period.

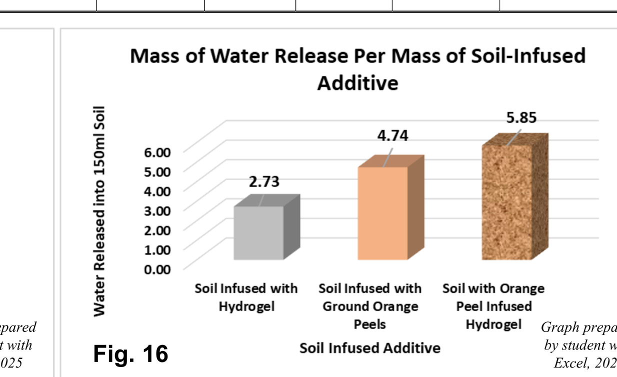
VII. Performance of the Orange Peel Hydrogel Infused Additives in Soil

Further analysis of the experiment outlined above was performed to evaluate how much water (in mass) was donated by the infused additives. Table 2. highlights the results discussed above, as well as the actual mass of water lost from the original 23.25ml of water in each 150ml soil sample (column 6, from left). Further, the mass of water donated by the infused additive is calculated (Fig. 15), and finally, the mass of water released per gram of Soil-Infused additive is determined (Fig. 16).

Table 2. Determination of Mass of Water Donated by Soil-Infused Additives (prepared by student with Excel, 2025)

Soil Type	Original % Moisture in 150ml Soil	Final 80 hour Soil % Moisture	Reduction from Original 15.5% Soil Moisture	% Water Loss	Water in Original Sample	Water Mass Lost (g)	Water Mass Donated by Infused Additive (g)	Mass of Infused Additive (g)	Mass of Water Donated per Mass of Infused Additive (g-H20/g-Additive)
Soil Alone	15.50	7.20	8.30	53.5%	23.25	12.45	X	X	X
Soil Infused with Hydrogel	15.50	9.13	6.37	41.1%	23.25	9.56	2.90	1.06	2.73
Soil Infused with Ground Orange Peels	15.50	10.39	5.11	33.0%	23.25	7.67	4.79	1.01	4.74
Soil with Orange Peel Infused Hydrogel	15.50	11.10	4.40	28.4%	23.25	6.60	5.85	1.00	5.85





Graph prepared by student with Excel, 2025

These results indicate that the OG-HG was best at providing moisture to the soil, so that soil-moisture could be maintained during arid conditions, to promote enhanced crop growth.

Discussion/Conclusion

Nearly 70% of the world's freshwater is consumed by agriculture. In light of water deficiencies, agricultural use of our water supply must become more efficient, while maintaining the necessary increase in crops, due to demands of a growing population. This research has created a unique Orange-Peel-Hydrogel (OP-HG) soil additive, that time-releases water into the soil, to decrease crop watering frequency, or maintain crop soil moisture during arid conditions. To begin the investigation, initial experiments evaluated the water content of various waste fruit peels. Orange, banana, and apple peels were shown to slowly release their water content over 13 days. Comparative analysis of original water content of these three peels demonstrated that orange, banana, and apple peels contained 88%, 82%, and 75% water. SEM, EDS, and ATR-FTIR analyses of the "wettest" two peels, orange and banana, highlighted that the OP surface is far more porous, which would promote useful water transfer to soil, while simultaneously releasing the many inherent soil nutrients contained within. Purposeful rehydration of dried OPs demonstrated that it can absorb as much as twice its original weight, slightly better than bananas. As such, OP became the natural additive of choice, to improve the water-releasing capabilities of methyl cellulose hydrogels. The new OP-HG contained 1.2% OP-infusion via sonication and was blended into 15.5% moisture soil (at 1g-OP-HG per 150ml of soil), This, and similar infusions of OP, HG, and control no-additive soil, were permitted to dry under daylight sunlight for 80 hours, without further watering, and the %-moisture was recorded for each throughout. The %-moisture of OP-HG-infused soil decreased from 15.5% to 11.10%, which is far less than the control soil, which decreased to 7.2%. Comparing total water loss, the OP-HG soil lost 28.4% of its water, while the control and HG-infused soils lost 53.3% and 41.1%, respectively. Considering the mass of water donated "per gram" of each soil-infusion-additive tested, OP-HG provided 5.85 g-H2O/g-OP-HG, compared to only 2.72g-H_2O/g-HG. This >2-fold increase in water release for OP-HG is attributed to the inclusion of orange peels. Regarding the water-savings potential of the OP-HG, each acre of corn crops requires 9000 gallons-water per day, or 63,000 gallons per week, during peak water use of dry, sunny, hot days. Use of OP-HG-infused soil would save ~8000 gallons per acre, per week, which is considerable, while simultaneously adding growth nutrients of Mg, Ca, P, and K (from the orange peel) into the soil.

Future Research

Future research would consist of testing the OP-HG in an agricultural environment, where OP-HG is mixed throughout the soil along with plant seeds and water. This mixture would then be watered every 6 days to track plant growth. Further investigation is required regarding how the OP-HG would affect the plant's growth, nutrients, etc.