A Waste-to-Water Radiative Cooling System for Off-Grid Atmospheric Water Harvesting

Waste to Wealth

Shahad R. Alasbali
shahad.alasbali@gmail.com

Mentor: Shakeel Ahmad
shakeel.ahmad@kaust.edu.sa

PI: Prof. Qiaoqiang Gan
Sustainability and Photonics Energy Research (SuPER) Lab
PSE Division

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Abstract

While waste materials are beneficial in our everyday life, after consumption they are only harmful to the environment. Realistically speaking, waste production and usage cannot be just abandoned completely as they play a crucial role in the industry. But the least to be done is to recycle them. One way to do so is to integrate them into an off-grid atmospheric water harvesting (AWH) system. This waste management method contributes to solving two problems: scarcity of natural water resources, and waste pollution as a part of the circular economy; turning waste into a resource. Experiments show that waste materials have an ability to be a part of sustainable, free-energy systems that are used to harness vapor water from humidity, for this harnessed water to be used in different applications in the field of renewable energy.



Figure 1: AI generated image, titled: *Waste to Wealth*

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1 Introduction

Nowadays, and more than ever, the world's efforts are focused on the Sustainable Development Goals (SDGs); a universal call to action 2. 17 interconnected goals put towards achieving a sustainable future for everyone by the year 2030.



Figure 2: The SDGs at the entrance of Government Affairs building, King Abdullah University of Science and Technology (KAUST).

Kingdom of Saudi Arabia is doing so as well, working towards a sustainable future, especially when two main problems emerge like a relatively high portion of waste materials is being produced daily in a geographical spot that hasn't been blessed with many natural water sources 3. So, the need for water sources' diversity arises, as well as the necessity of adopting waste management methods.

Previously [**zhou2021hybrid**], an atmospheric water harvesting method has been addressed, using materials with a passive radiative cooling property in a double-sided

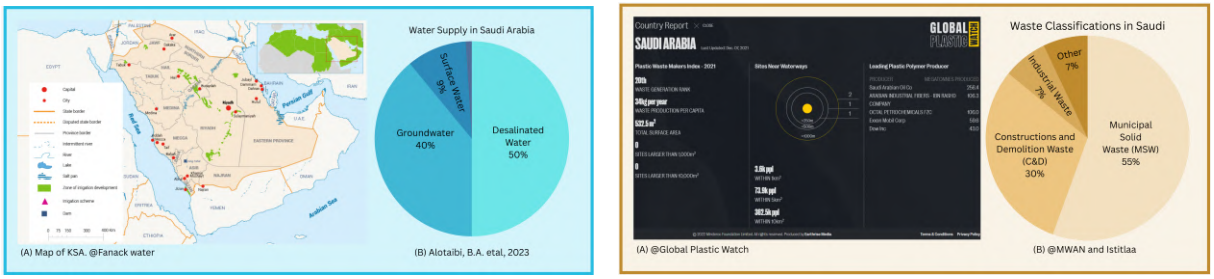


Figure 3: (a) Geographical distribution of natural water resources in Saudi. (b) Different categories of water sources and their proportional contributions to the overall water supply in Saudi. (c) Saudi has a waste generation rank of 20th and a per capita waste production of 34 kg per year. (d) Waste classifications in Saudi Arabia, where Municipal Solid Waste (MSW) makes up the largest portion at 55%.

architecture to cool itself below the dew point in highly humidified weather conditions then condense the atmospheric water formed as humidity on its surface.

In this project, same architecture [**ahmad2024lubricated**] has been used to test different waste materials by measuring their emissivity, transparency and reflectivity, and by observing their ability to achieve passive radiative cooling and condensate atmospheric water formed as humidity on their surfaces.

1.1 Objectives

- Find a new natural water resource.
- Waste recycling and management.
- Apply in renewable energy technologies.

2 Methodology

Radiative cooling is a natural process where the body loses heat by emitting thermal radiation. This is according to Plank's radiation law:

"Every object with a temperature above absolute zero continuously and spontaneously emits electromagnetic radiation, and this amount of heat emitted depends on the object's temperature and its ability to emit radiation, known as the emissivity ε."

Passive radiative cooling is a specific application of radiative cooling that involves designing a system or material to maximize this heat loss without using any external power of mechanical components. In this project, the material set as the emitter must be highly emissive within the atmospheric transparency window (ATW $\approx$ 8-13 μm, a band of mid-infrared radiation). This is a range of the electromagnetic spectrum where the Earth's atmosphere is relatively transparent, allowing the emitted heat to pass through into the cold outer space without being absorbed by the atmosphere itself. This helps the material to cool itself below the ambient temperature. For this, the architecture must be put directly under the sky.

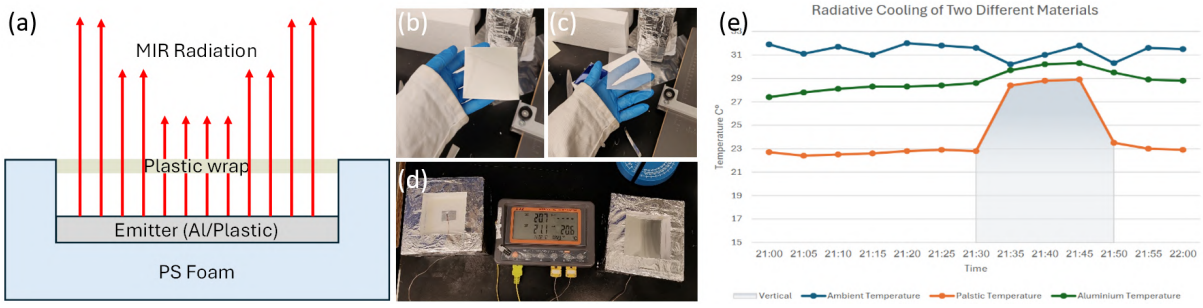


Figure 4: (a) The horizontal setup. (b) The Aluminum piece. (c) The plastic piece. (d) Final horizontal setup attached to a Digital 4k Type Thermocouple Thermometer. (e) Temperature changes over time for Al and plastic emitters.

2.1 Architecture Development

To generally decide on the emitter's materials, two samples from different categories of waste materials had been chosen: an Aluminum piece and a plastic piece 4. To test their radiative cooling they were set horizontally facing the sky.

4 shows that while the plastic sample can achieve radiative cooling given the drop in its temperature compared to the ambient air temperature, the aluminum sample on the other hand cannot. Also, the area highlighted in the graph from 21:30 to 21:50 illustrates that even the plastic emitter doesn't cool if it does not face the sky (as it was during the mentioned time vertically facing some other direction). When put back facing the sky, the plastic emitter cooled itself again.

For the emitter to be able to achieve the radiative cooling while vertical, a mirror must be added to reflect the radiation to the sky. And to increase the emitter's exposed surface area, a vertical double-sided architecture is used 5.

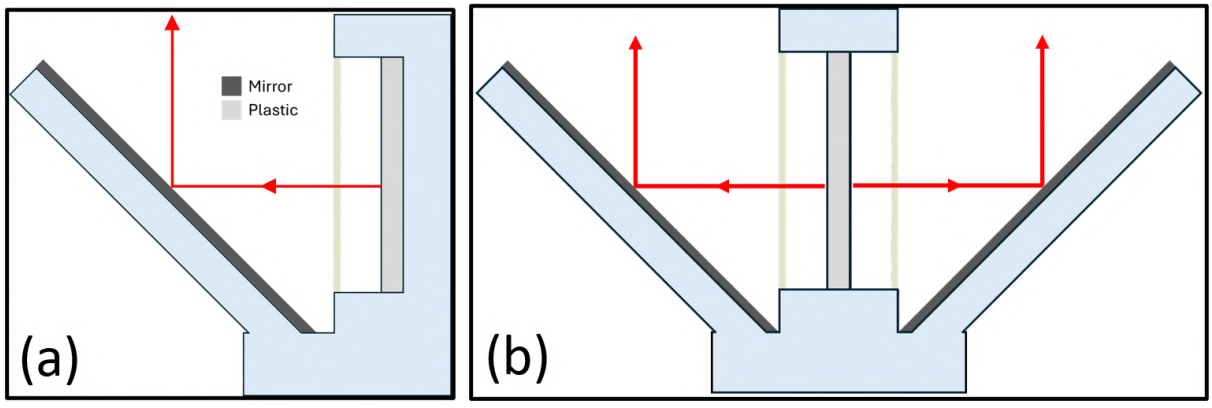


Figure 5: (a) A vertical setup with a mirror attached to it. (b) A vertical double-sided architecture.

2.2 Modified Architecture

While the purpose of the vertical double-sided architecture is to increase the surface area exposed to the ambient air, the thermal convection would affect the process of the emitter's radiative cooling. Hence, the emitter should be contained within a cover that has a high transparency within the ATW; so, it could prevent the thermal convection while allowing the emitter's radiation to pass through.

On the other hand, the humidified air must hit the emitter's surface for the atmospheric

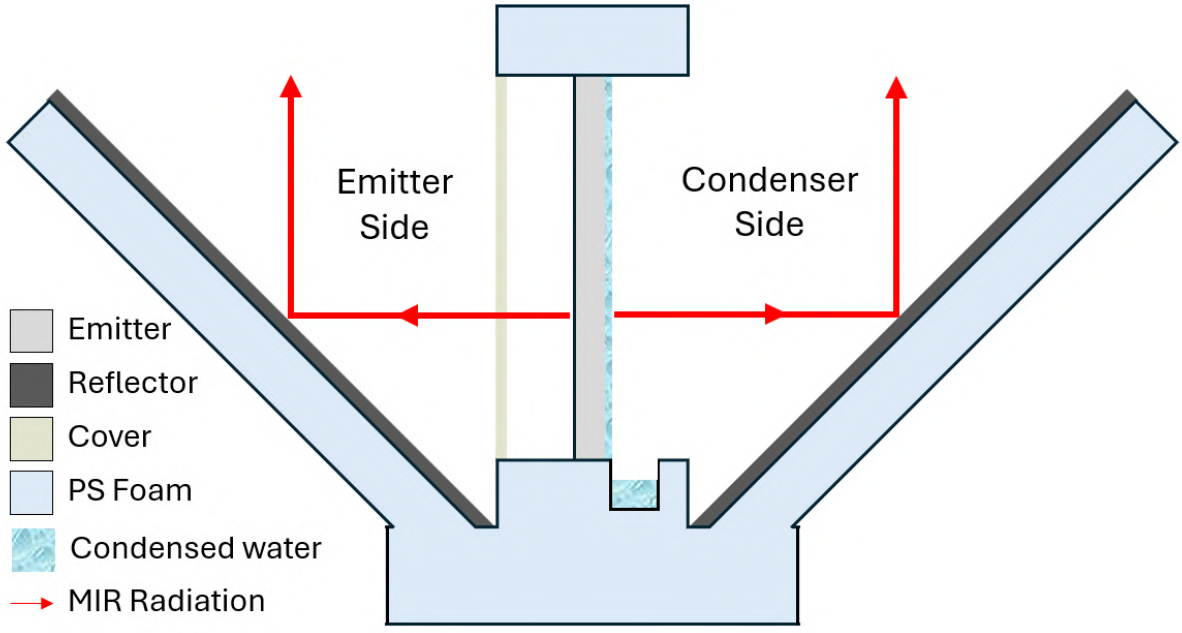


Figure 6: A side view of the used vertical double-sided architecture with the modifications needed.

water to condensate on it. To achieve this, one side of the emitter was covered with a see-through plastic wrap 6, and the other side was also covered by the same wrap but with holes in it for the humidified air to go into. While the condensation will happen on the side with the holes, on the fully covered side of the emitter a thermocouple thermometer was attached to it to measure its temperature.

This way, the emitter will be able to cool itself while also condensing atmospheric water. For the condensation to happen, the emitter's temperature must be equal to or less than the dew point. The dew point is the temperature at which moisture in the air starts to condensate on the surface, and it depends on the ambient temperature and the relative humidity (RH%), which is the amount of moisture in the air compared to what the air can "hold" at that temperature. The RH was recorded using a sensor accompanied the setup during the experiments, and the dew point was calculated using an online calculator.

2.3 This Project

In this project, different materials from everyday life-waste were used 7, such as:

1. Single use plastic as the emitter.
2. Plastic food wrap as the emitter's container.
3. Al food wrap as the reflector.

These materials have been chosen for the final setup based on their relatively high performance in several experiments regarding their emissivity (for the emitter), the transparency (of the container), and the reflectivity (of the reflector).

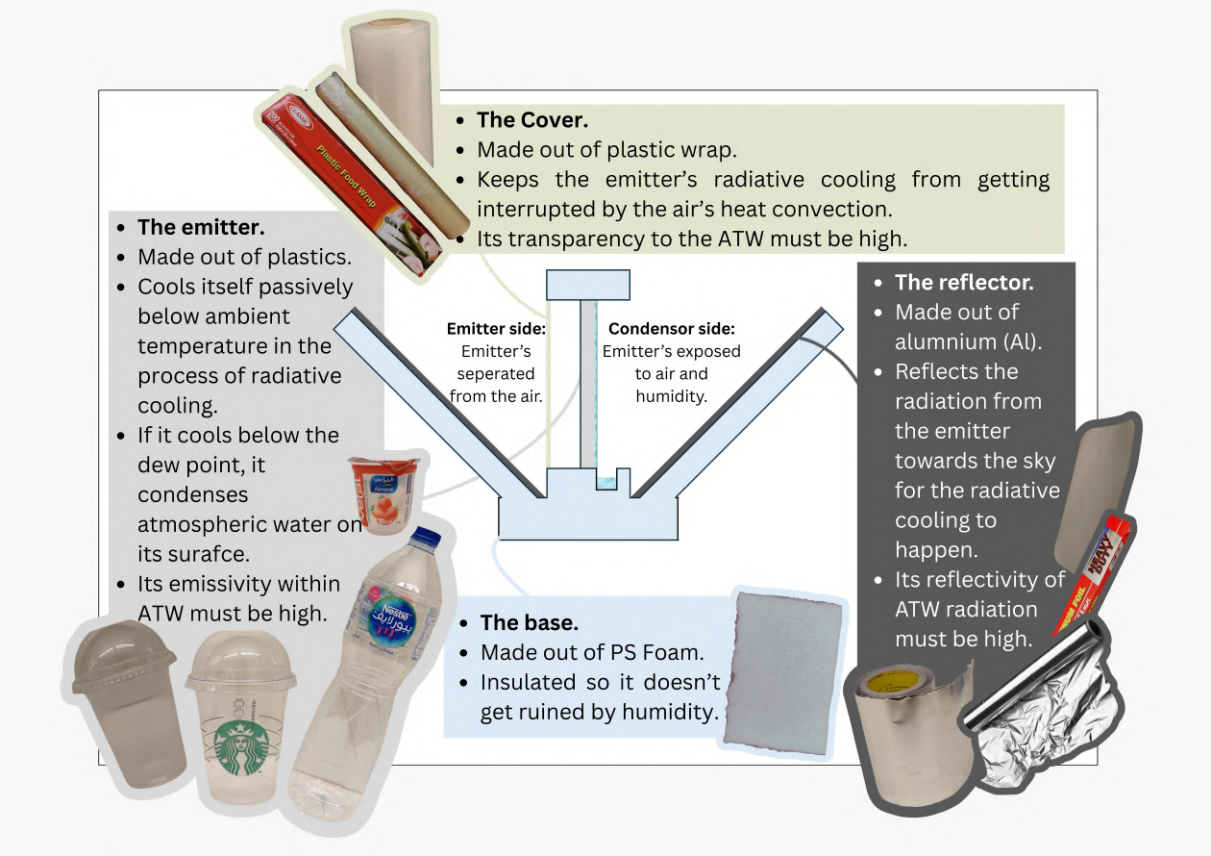


Figure 7: Different materials from everyday life-waste that have been tested for this project.

2.4 Data Collection

Data was collected in the lab using the Fourier transform infrared (FTIR) spectroscopy, and in outdoor experiments 8.

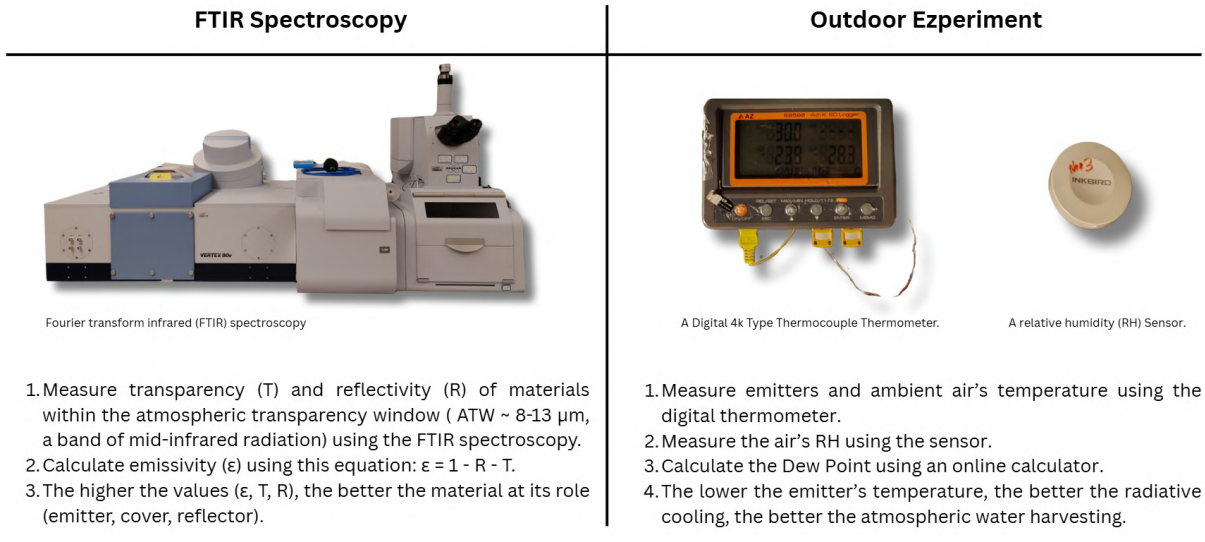


Figure 8: Methods of data collection.

2.5 Challenges and Obstacles

This project is based on outdoor experiments conducted in specific weather conditions, like high relative humidity. And while these experiments can be conducted indoors by injecting an artificial humidified air flow inside the setup, and using liquid nitrogen as the cold source (to represent the sky in the process of passive radiative cooling),still, this project is a solution found to be used in real life situations.

3 Results

3.1 Emissivity

For this step, 4 different plastic waste materials were chosen randomly based on the frequent everyday consumption of plastics in the campus diner at KAUST. These plastics are: A Pure Life Water Bottle (polyethylene terephthalate 'PET'), a Starbucks one-use plastic cup with the logo on (polypropylene 'PP'), a random plastic cup, and an Almarai yogurt container.

For the material to be appropriate for radiative cooling it must have a significantly high emissivity. These materials were characterized using the Fourier transform infrared (FTIR) spectroscopy 8. This spectroscopy is a technique used to obtain an infrared spectrum of absorption or emission of a solid, liquid, or gas. To know the emissivity ε of a material, its transparency and reflectivity got to be measured by this device, then the emissivity of a specific range of the spectrum can be calculated using this equation:

$$\varepsilon = 1 - R - T$$

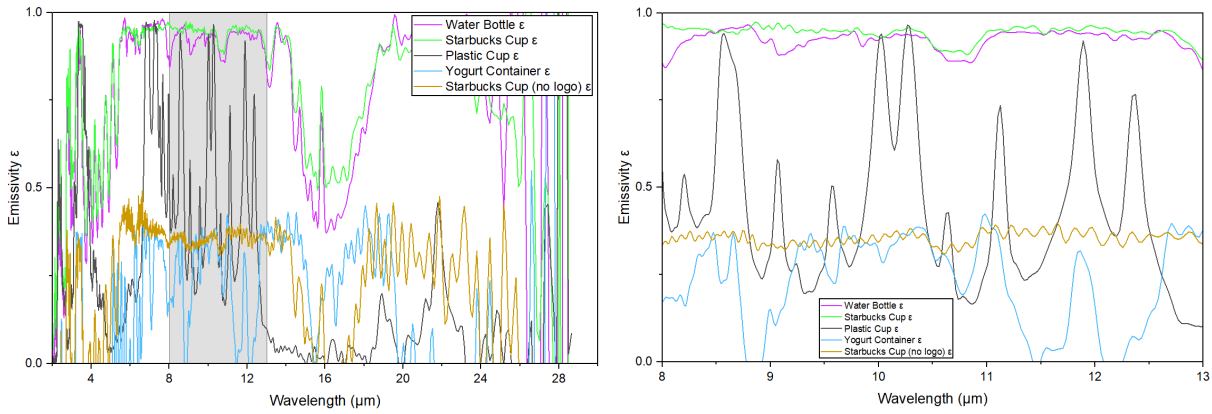
Where ε is the emissivity which is the measure of a material's ability to emit energy as thermal radiation, T is the transparency which is the property of a material that allows light to pass through it without being scattered, and R is the measure of the material's ability to reflect the incident electromagnetic radiation.

FTIR data 9 shows that the Sturabucks' logo has the highest emissivity among other samples within the ATW. Comes right after it the Water Bottle sample with a difference of only 0.2. Next is the random plastic cup with about a 50% drop in the emissivity. At last, comes the yogurt plastic container with a huge difference in emissivity 1.

Emitter	Emissivity
Starbucks Cup (logo)	0.94
Water Bottle	0.92
Plastic Cup	0.40
Starbucks Cup (no logo)	0.35
Yogurt Container	0.24

Table 1: Average emissivity of different emitters measured by the FTIR spectroscopy.

Outdoor experiment was conducted to test the radiative cooling of the above emitters and to test their ability to condensate atmospheric water for 30 minutes under the following weather conditions: $T_{\text{amb avg}} = 30.76°\text{C}$ and $RH_{\text{avg}} = 89.68\%$. While the Water Bottle sample has an emissivity slightly lower than the Starbucks' logo proven by



(a) (b)

Figure 9: (a) FTIR characterization of emissivity of different emitters' plastic samples within the whole spectrum. (b) Emissivity within the atmospheric transparency window

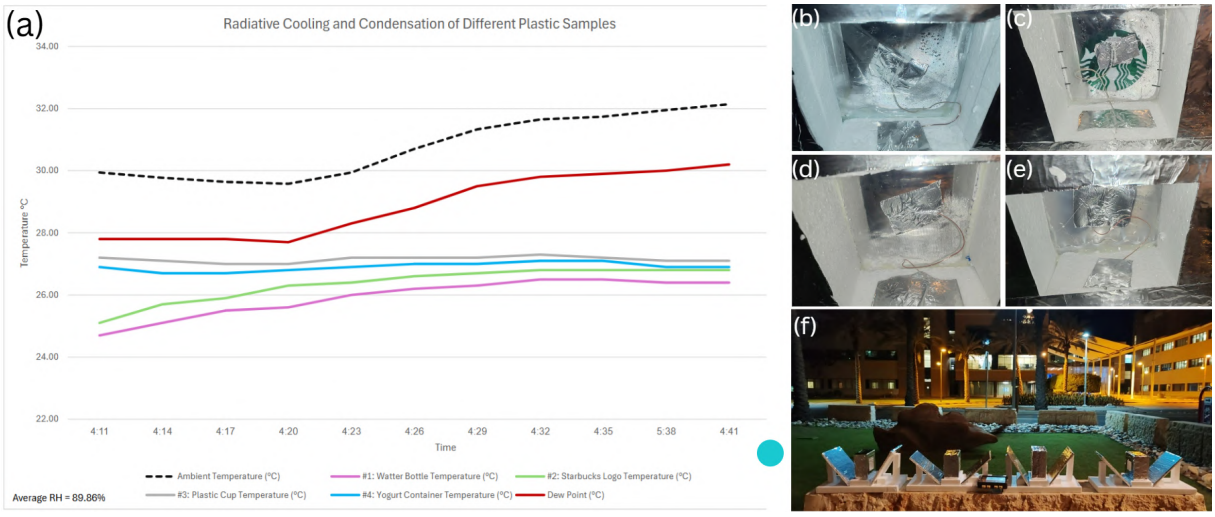


Figure 10: Keeping the standard cover and reflector and only testing the emitters. (a) Outdoor testing of the emitters' ability to achieve radiative cooling and atmospheric water harvesting (condensation) on the emitters' surfaces: (b) water bottle (c) Starbucks logo (d) plastic cup and (e) yoghurt container. (f) experiment setup where average RH = 89.86%.

the FTIR spectroscopy, outdoor experiment showed that it has a higher rate of radiative cooling compared to the Starbucks' logo; this is due to the larger surface area of the water bottle compared to the Starbucks' logo which gives the water bottle a privilege needed to achieve a better AWH. More importantly, all plastic samples showed the ability to condensate atmospheric water in previous weather conditions 10.

3.2 Transparency

A plastic food wrap was used as a container of the emitter. FTIR characterization showed an average transparency of this material equal to 0.70 within ATW, which is 21% less than the transparency of the standard material which has a transparency equal to 0.91.

A 1_{st} outdoor experiment 11 was conducted for 60 minutes in these weather conditions:

$T_{\text{amb avg}} = 32.92°\text{C}$ and $RH_{\text{avg}} = 77.91\%$ showed a $T_{\text{avg}} = 30.19°\text{C}$ for the plastic food wrap, and $T_{\text{avg}} = 29.94°\text{C}$ for the standard material, showing a drop in the performance of the radiative cooling due to the decreased transparency of the plastic wrap compared to the standard material.

Another outdoor experiment 11 was conducted for 20 minutes under $T_{\text{amb avg}} = 33.12°\text{C}$ and $RH_{\text{avg}} = 80.79\%$ showed a $T_{\text{avg}} = 31.37°\text{C}$ and $T_{\text{avg}} = 30.76°\text{C}$ for the plastic food wrap and the standard material respectively, which gave the same result.

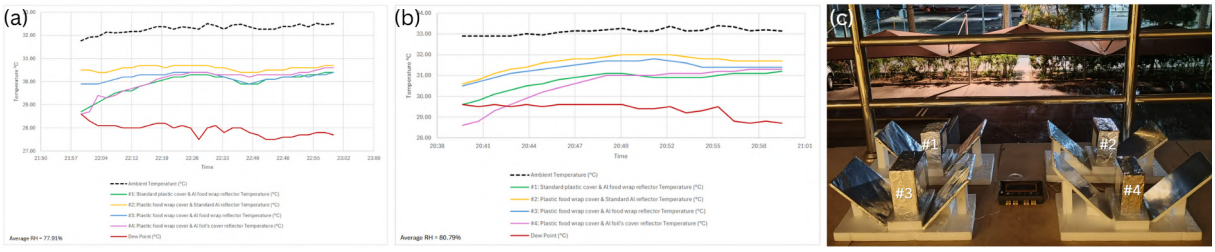


Figure 11: Fixing the water bottle as the emitter and changing the reflectors and covers. (a) Outdoor testing of the ability to achieve radiative cooling in an average RH = 77.91% and (b) RH = 80.79%. (c) Experiment setup.

3.3 Reflectivity

For the reflectivity, two Al samples were tested: an aluminum food wrap, and an aluminum foil's cover. FTIR characterization showed an average reflectivity equal to 0.99 for the Al food wrap. As for the foil's cover, it is equal to 0.73, and a reflectivity of 0.97 for the standard reflector. To be more specific, the flat shiny face of the Al food wrap has a reflectivity equal to 0.99, which is the highest value among all samples. Where it has a reflectivity of 0.96 when it is wrinkled. For the matt-face of the Al wrap, it has a reflectivity equal to 0.98 12.

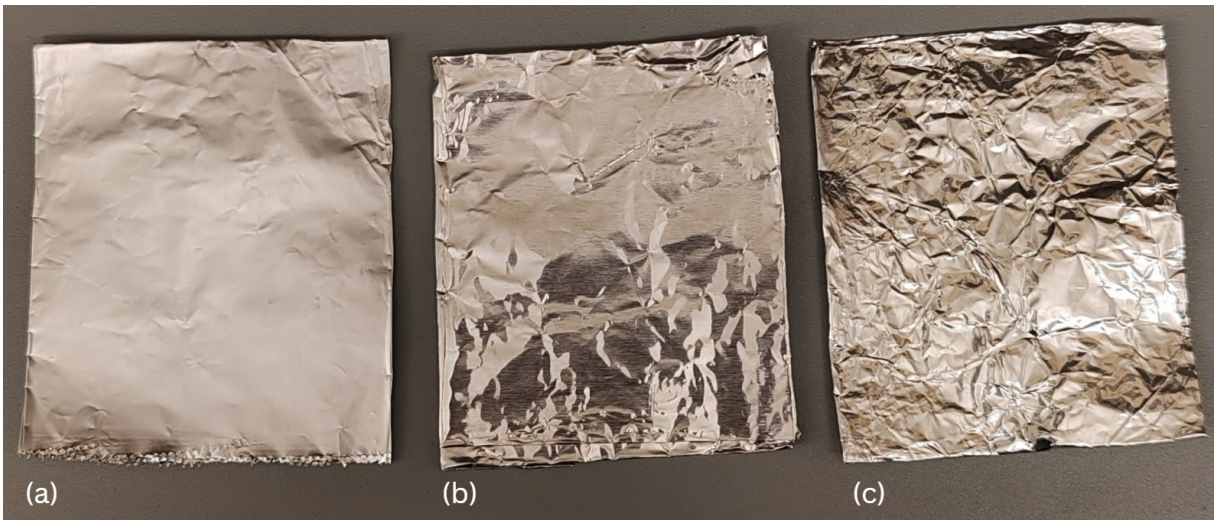


Figure 12: Al wrap. (a) Shiny face. (b) Matt face. (c) Wrinkled face.

Previous 1_{st} outdoor experiment 11 showed a $T_{\text{avg}} = 30.58°\text{C}$ for the standard reflector, $T_{\text{avg}} = 30.19°\text{C}$ for the Al food wrap, and $T_{\text{avg}} = 30.06°\text{C}$ for the Al foil's cover reflector, showing that the last had the best performance among them.

2_{nd} outdoor experiment 11 showed same final results, showing that the Al foil's cover got

the better reflectivity equal to $T_{\text{avg}} = 30.56°\text{C}$, then the Al food wrap with a performance equal to $T_{\text{avg}} = 31.37°\text{C}$, followed by the standard reflector $T_{\text{avg}} = 31.63°\text{C}$.

4 Discussion

Waste materials showed good ability to achieve the radiative cooling 13.

By FTIR, both Starbucks logo and the Al food wrap had the highest values of emissivity and reflectivity respectively. **In outdoor experiments**, the water bottle and the Al foil's cover are the ones with the highest rate of radiative cooling. This variation in results is due to many factors such as surface area and smoothness.

Even though the Starbucks logo had the highest emissivity, rest of the cup showed a significant drop in emissivity. This requires more investigation of the properties of the cup. And although different waste emitters showed different rates of radiative cooling, they all were able to condense atmospheric water in high RH weathers.

Role	Waste		FTIR (within ATW ~ 8-13 µm)			Experimental
	Image	Name	Emissivity (ε)	Reflectivity (R)	Transparency (T)	Temperature °C
Emitter		Water Bottle (polyethylene terephthalate 'PET')	0.92	0.064	0.017	25.93
		Starbucks Cup (logo) (polypropylene 'PP')	0.94	0.045	0.013	26.35
		Starbucks Cup (no logo)	0.35	0.625	0.022	
		Plastic Cup	0.40	0.054	0.544	27.1
		Yoghurt Container (polypropylene 'PP')	0.24	0.622	0.133	26.9
Cover		Standard			0.91	30.35
		Plastic Food Wrap (polyvinyl chloride 'PVC')			0.70	31.11
Reflector		Standard (Al)		0.97		31.11
		Al Foil's Cover (Al)		0.73		30.31
		Al Food Wrap (aluminum alloy)		0.99		30.78

Figure 13: Overall results of emissivity, transparency and reflectivity both in lab and outdoor experiments.

5 Conclusion and Future Work

This project is a sustainable method to recycle our everyday-life-waste materials by using them in an atmospheric water harvesting system.

For a better AWH, the following should be considered:

- Materials with high emissivity to set as the emitter.
- Larger surface area of the emitter.
- High transparency of the emitter's container.
- High reflectivity of the material acting as the mirror.
- A high relative humidity.

The higher and better these values are, the better and more efficient atmospheric water harvesting will be. And while this architecture is meant for the night-time AWH, it can be modified to daytime AWH by using a spectral selective mirror to prevent the emitter from heating due to the sun incident radiation.

5.1 Applications in the field of renewable energy

While water plays a huge role in a lot of applications, even those meant for living needs, here are some of major application harnessed atmospheric water from this system can a be a significant part of.

5.1.1 Hydrogen production via electrolysis

Hydrogen plays an important role in the renewable energy sector. Hydrogen is a clean energy carrier that can be produced from water, where itself can be used in a various range of applications.

5.1.2 Enhancing Solar Photovoltaic (PV) Panel Efficiency

Harnessed water can be used to increase the efficiency of the PV panels by the passive cooling where the water is put on the back of the PV panel for its evaporation to help the panel to cool down and dissipate heat as it affects its efficiency, and for the active self-cleaning is a gravity-driven system that allows the water droplets to slide on the PV panel's surface and clean it from the dust and dirt on it to increase its energy output.

5.1.3 Off-Grid Living and Micro-Grids

This atmospheric water harvesting system, combined with a renewable energy source like solar, provides both clean water and energy; the two most fundamental needs for off-grid living.

6 Acknowledgement

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7 References

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8 Poster

