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Zero-Energy and Low-Cost Kirigami-Based Hydrogel Composite Dehumidification System

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Abstract
Humidity coupled with high temperatures poses a serious health threat to millions of people worldwide. High humidity prevents perspiration, significantly increasing the risk of hyperthermia. The humidity of indoor spaces can be controlled with dehumidifiers or air conditioners, but these are often expensive, energy intensive, and not viable for the billions of people living in poverty around the world. Our novel method of dehumidification uses a kirigami structure coated with desiccant material that can be installed on windows or fan units while using little to no electricity. The kirigami structure increases surface-air contact, enhancing the adsorption of water vapor by the desiccant material composed of a hygroscopic salt ($CaCl_2$) infused in a polymeric hydrogel matrix and doped with polymer hollow spheres and metal organic frameworks. Once saturated, the material can be easily regenerated at temperatures near 70°C, achievable with a solar collector or simply drying under sunlight to be used over many cycles. It is able to adsorb nearly three times as much water as silica gel, reaching adsorption of 90% of its mass, making it viable for large scale dehumidification in 75% relative humidity (RH) or above. Cyclic testing has also shown stable performance over at least five 2-day adsorption cycles. This development could allow for more affordable and accessible humidity control for people around the world, especially in tropical regions where the average humidity can exceed 85% RH.

Introduction

The Problem with Humidity

Excessive heat and humidity is the leading cause of death in weather-related accidents,[1] and is especially fatal in tropical low-income regions without access to air conditioning. Heat-related illness, or hyperthermia, occurs when the body is unable to cool properly. Sweat evaporates to release excess heat, but when humidity is high, high atmospheric vapor pressure prevents evaporation. A 20-year study by researchers in Australia and China found that 480,000 deaths occurred annually on average due to extreme heat and humidity.[2] Furthermore, heat-related deaths are on the rise, with a 56% increase in the number of deaths in the three-year span of 2018 to 2021.[3] High humidity and temperatures also have devastating effects beyond heat health risks. A study in India found that there is an approximate 3% decrease in India's GDP for every increase in degree Celsius.[20] Furthermore, a study by scientists at NREL found that more than 50% of energy consumption by AC is due to humidity.[21] Climate change will continue to exacerbate these problems as average global temperatures rise due to greenhouse gas emissions. The US National Oceanic and Atmospheric Administration reports that average global temperatures can be expected to rise by up to 9.7°F by the end of the century.[4] Most importantly, AC and dehumidifiers are too expensive for low-income communities living in tropical areas. Of the 2.8B people living in the hottest regions around the world, only 8% have access to AC.[22]

Current Solutions

Current research and solutions on the market are: refrigerant systems, desiccant systems, and low energy materials. Refrigerant systems have been designed with solar-assisted cooling systems,[7] vapor compression,[8] evaporative cooling,[9] heat pump systems,[10, 11] and more, in order to condense humidity based on temperature differences. Traditional desiccants, such as silica gels, hygroscopic salts, and other deliquescent liquids have also been well documented as a means of dehumidification through salt absorption.[6] Hybrid hygroscopic salts (such as $CaCl_2$ + LiCl or

Triethylene glycol + LiCl) have also shown promising results. Furthermore, fibrous membranes combining desiccant and photothermal layers have been designed to actively adsorb, hold, and evaporate moisture using sunlight.[12] Hygroscopic salts in solid form have also been used, but deterioration of these salts over use, such as particle clustering, quickly degrades humidity collection efficiency.

Each of these systems and material designs have varying inadequacies, including high energy consumption for desorption, varying deficiencies at different humidities and temperatures in collection capacities, and cost. None have yet demonstrated performance that sufficiently counteracts the costs of required energy consumption or expensive materials for targeting low-income communities.

Table I. Quantifying the benefits of Pouragami over current alternatives.

|	Air Conditioning	Dehumidifiers	Mechanical Fans	Non-electrical dehumidification	Pouragami
Affordability	$6000 ($4000/10 yrs)	$1000 ($2000/10 yrs)	$200 ($400/10 yrs)	0.062–0.86 $/L => $3000/10 yrs	$600/10 yrs
Requires Electricity?	Yes	Yes	Yes	No	No
Energy cost	$600/yr	$360/yr	$60/yr	$0	$0
Efficiency	30L/day	25L/day	No change in humidity	6L/kg/day	Goal: 2L/kg/day
Ease of Use	Scalable	Scalable	Scalable	Has to be stacked horizontally	Can be installed vertically
Lifetime	15 years	5 years	5 years	10 cycles (10 days)	Goal: 15 days
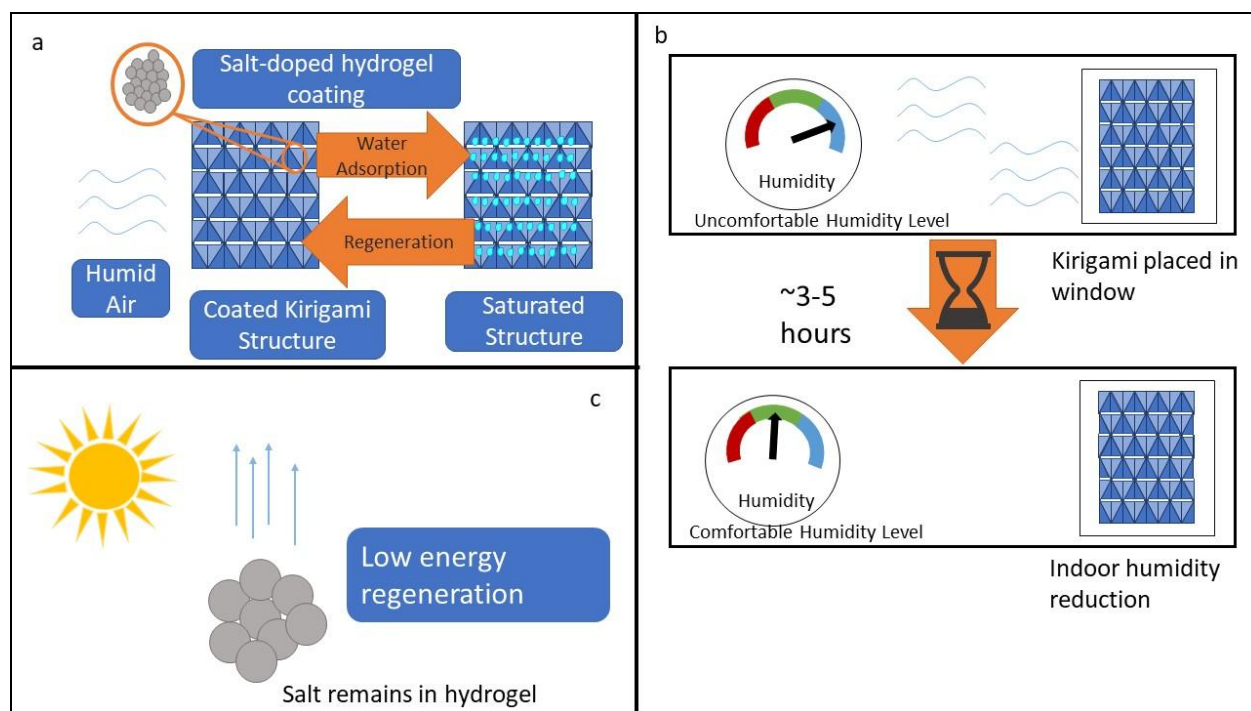
Figure 1: Initial vision figure. a) The coated kirigami allows for cyclic humidity absorption. b) Placed in a window, the coated kirigami could reduce a room's humidity to comfortable levels. c) After saturation, solar energy could be used to regenerate the desiccant material.

Summary
We have developed a composite material for dehumidification that is composed of a mixture of polyacrylamide (PAM), poly(N-isopropylacrylamide) (PNIPAM), $CaCl_2$, and polymer hollow spheres (PHS). The composite can be coated on a folded kirigami sheet made of aluminum-coated polyethylene terephthalate (PET).

Economic, Environmental, and/or Global and Social Contexts
This project had both environmental and social pillars. As already discussed, high humidity in conjunction with high heat poses a significant health risk, so having ways to mitigate this is important. Of existing dehumidification methods, most are cost-prohibitive for many, in terms of both upfront costs and energy costs. The high energy use of most dehumidifiers and air conditioners was also a primary motivation for our project, as reducing energy consumption inherently leads to lower emissions and slows climate change.

Ethical Issues
All five components of our composite would be sourced ethically. The vendors from which we purchased each of our materials abide by ethical practices in sourcing, manufacturing, and shipping. In addition, our solution is safe when handled or in use. From our testing, our composite material is inert under atmospheric conditions. Small amounts of the salt may leach out of the composite over continued use of our solution, but this is not a health concern (will only affect efficiency). When efficiency has decreased significantly, we propose that the

composite material be returned to us where we can reintegrate the salt for reuse. Moreover, the kirigami backbone can be reused and we are aware that certain hydrogel matrices and polymer hollow spheres are capable of recycling. Since our time working on our project was limited, we were not able to attempt recycling our material but are confident that we could develop a method for recycling or find alternative materials to make the end of life stage for our solution sustainable.

Materials and Methods
Hydrogel Synthesis
For the PAM reaction, acrylamide (AM), N,N'-methylenebisacrylamide (MBA), tetramethylethylenediamine (TMED), and ammonium persulfate (APS) were purchased from Sigma-Aldrich. The PNIPAM reaction used the same reagents, but with N-isopropylacrylamide (NIPAM) instead of AM, also purchased from Sigma-Aldrich. Anhydrous $CaCl_2$ was purchased from Sigma-Aldrich and was included in both formulations. ROPAQUE^{TM} Ultra EF polymer hollow spheres (PHS) were purchased from Dow and diluted with DI water from 30% to 15%. Stock solutions of each monomer were prepared with two different monomer to crosslinker (MBA) ratios: 350 mg of monomer to 30 mg MBA ("350") or 750 mg of monomer to 30 mg MBA ("750"). 1 mL of TMED was mixed into each stock solution, and both were stirred constantly for five hours. APS solution was prepared with 20 mg of APS for each mL of water.

Samples were prepared by taking 5 mL of one stock solution to form a single polymer or 2.5 mL of each to form a 50:50 blend of PAM and PNIPAM. The mixtures were stirred with $CaCl_2$ of mass equal to 30%, 40%, or 50% the combined mass of monomer and crosslinker. Stirring constantly, a small amount of the 15% PHS suspension or 120 mg of MOF was added to the reaction vessel and diluted with DI water to achieve the desired concentration. To initiate polymerization, 1 mL of APS solution was added to the mixture, and the final mixture was quickly poured into a circular well plate to cure. Samples were placed in an oven at 70°C to dry overnight.

Polymer Hollow Spheres
PHS of 1 micron diameter from Dow Chemical that are typically used as a paint coating will be impregnated with $CaCl_2$ then dispersed in the hydrogel precursor solution at varying concentrations of 1.5%, 3%, and 4.5 wt%.

Metal Organic Framework (MOF)
MIL-101(Cr) MOF nanoparticles are synthesized according to Refs. 23 and 24. The resulting nanoparticles are tested with existing concentrations of PAM, PNIPAM, and other parameter components, at the concentration designated by Ref. 23 at 16 wt%.

Kirigami
Aluminum coated PET sheets were cut and scored with a Cricut Air 2 cutting machine using a premade template. Cut material was removed and the resulting scored sheet was folded to produce the desired kirigami shape.

Humidity Testing

After drying, the mass of each sample was recorded. Samples were placed in an acrylic chamber with dimensions 1' x 2' x 1'. Compressed air was bubbled through a saturated solution of potassium chloride and plumbed directly into the chamber to provide constant humidity. A hygrometer probe was inserted in the chamber to measure the relative humidity within. Flow was controlled to vary the relative humidity from around 75% to around 90%, the typical humidity of our targeted regions. All access ports to the chamber were sealed with tape. Samples were periodically removed from the chamber and their masses recorded. Increases in mass were taken to be the mass of water absorbed from the air. This mass was divided by the dry mass of the sample to determine water absorption in grams of water per gram of sample. Samples were placed back into the chamber to continue absorption. To regenerate for subsequent absorption cycles, samples were placed in an oven at 70°C and allowed to dry overnight to simulate solar regeneration.

Results and Discussion

Desiccant Selection Background

Previous work using kirigami structure took advantage of the way in which air currents interact with the geometry to collect fog (water droplets suspended in air). While we expect that these dynamics will enhance water absorption on a large scale, our aim is to adsorb water vapor from the air. Hence, a desiccant coating is necessary to adsorb water on the scale we're interested in. An ideal desiccant for our purposes must fulfill the following criterias: 1) High absorption capacity (more than 2g/g), 2) Low regeneration temperature and energy requirements (lower than 80°C), and 3) Low cost (less than $10/unit). Multiple desiccant types such as silica gel, zeolites, MOFs, and hygroscopic salts have been considered for this project. Silica gel is a widely used desiccant in traditional dehumidification systems for its affordability and low regeneration temperature. However, its low adsorption capacity (0.4g/g) makes it unsuitable for our application. Zeolite, another commonly used commercial adsorbent, also demonstrates deficient adsorption capacity. While it is capable of adsorption at very low humidity, its high regeneration temperature of 300°C makes it inappropriate for our application. MOFs are a type of crystalline porous materials made by joining metal units with linkers, which has demonstrated superior performance in all aspects, it has been proven hard to synthesize. Its high cost is a deterring factor, but we would like to try this state of the art material and perform the efficiency to cost tradeoff. Finally, hygroscopic salts such as LiCl, $MgCl_2$, and $CaCl_2$ exhibit high adsorption performance (5-6g/g) via hydration reaction. They are also readily available at low cost. However, the formation of crystalline hydrates drastically decreases their performance and kinetics after a certain degree of saturation and the high energy consumption for regeneration prevents them from being used on their own. Moreover, due to the vertical nature of our kirigami structure, standalone salts cannot adhere to the substrate, especially once they have adsorbed moisture and dissolved. The comparison between these materials are summarized in **Table II** below.

Table II: Comparisons of various desiccant types.

	High adsorption capacity (>2g water / g desiccant)	Operation at low humidity (<30% RH)	Low regeneration temperature (<80°C)	Low cost (<$10/final unit)
Silica Gel	✗	✗	✗	✔
Zeolites	✗	✔	✗	~
MOFs	✔	✔	✔	✗
Salts	✔	✔	✗	✔
Salt Composites	✔	✗	✔	~

Hence, we turn our attention to salt-infused porous matrices and hollow spheres. The supporting matrix will allow the hygroscopic salts to stay in solid form and take advantage of the matrix's mechanical stability. Xu Zheng *et al.* has demonstrated that salt composites are suitable dehumidifiers for most climates and building types, matching our target market segment. The chosen salt is $CaCl_2$ for its high adsorption capacity from their low vapor pressure and availability. While LiCl has demonstrated superior adsorption capacity due to its lower vapor pressure, $CaCl_2$ regenerates more readily and is cheaper. Our key requirement for the host material, then, is to prevent salting-out or leaching. That is, the material must be able to retain the salt during desorption. The three chosen materials for this project are: Hydrogels, Polymer Hollow Spheres (PHS), and Metal Organic Frameworks (MOFs), all infused with $CaCl_2$.

PAM
Polyacrylamide (PAM) is the first of the hydrogels that we used. Being a hydrogel, its porous structure swells in water. PAM is super-absorbent and can hold a large volume of water. We hoped to take advantage of this property to create a system with a large storage capacity for absorbed water.

PNIPAM
Poly(N-isopropylacrylamide) (PNIPAM) is also a hydrogel, and as such also swells in water. More notably, PNIPAM has thermo-responsive properties that cause it to change conformation at different temperatures. At low temperatures, the structure of PNIPAM is such that its hydrophilic groups are able to readily absorb water. Once heated above 32°C, it begins to change conformation, presenting hydrophobic side groups to the stored water and squeezing the water out. The rate of this is slow until temperatures get even higher, around 60°C-70°C, which are still well below the boiling point of water. This allows us to potentially regenerate the material after an absorption cycle with only solar energy, with the aid of a solar collector.

PHS
We expect the salt to stay inside the pores and uniformly disperse across the coating. Furthermore, the confinement of water molecules inside the PHS will decrease its vapor diffusion length 2-3 orders of magnitude shorter than hydrogel matrices, enhancing adsorption kinetics. The polymeric hollow spheres are also expected to be able to swell and serve as water storage (they are supplied with water inside, where the water can be evaporated) increasing the absorption capacity similarly to the hydrogels. Its adhesive nature and easy application to a substrate is also a desired characteristic.

MOF
According to Ref. 23, the inclusion of MOF nanoparticles serve to enhance the sorption efficiency of water vapor. The structure of the MOF nanoparticle allows fast sorption kinetics and high equilibrium water uptake due to its zeotype structure with compatible mesoporous cage sizes (diameters of 29 and 34 Å) and microporous window sizes (diameters up to 16 Å), which are accessible to water molecules. We successfully observed the benefits of including MOF nanoparticles in our recipes as shown in Figure 3. The 750 PNIPAM and MOF recipe outperformed the next best recipe by ~ 20% (measuring at the 24 hour mark). We also observed spontaneous seeping of water as described in Ref. 23 where water beaded up on the top surface of the hydrogels, but did not get to quantifying seeping amounts in our experiments.

Absorption Data
To find the best hydrogel formula, different monomers to crosslinker ratios and monomer blends (PAM vs. PNIPAM vs. both) were tested, holding salt and absorption enhancers concentrations constant. Results from a 96 hour absorption cycle at 75%RH are shown in **Figure 2** below. The maximum absorption of silica gel (0.33 g/g) is shown as a dashed line. Holding the salt concentration at 30 wt% and 3 wt% PHS, the two best-performing samples were 750 PNIPAM and the 350 PAM-PNIPAM blend, absorbing 0.59 g/g and 0.52 g/g, respectively at saturation. These represent a near doubling of the absorption capacity of silica gel, though over a longer period of time. The absorption rate is maximized at 24 hours and starts decreasing thereafter. This lets us define 1 cycle as a day, after which the composite can be regenerated for the next cycle.
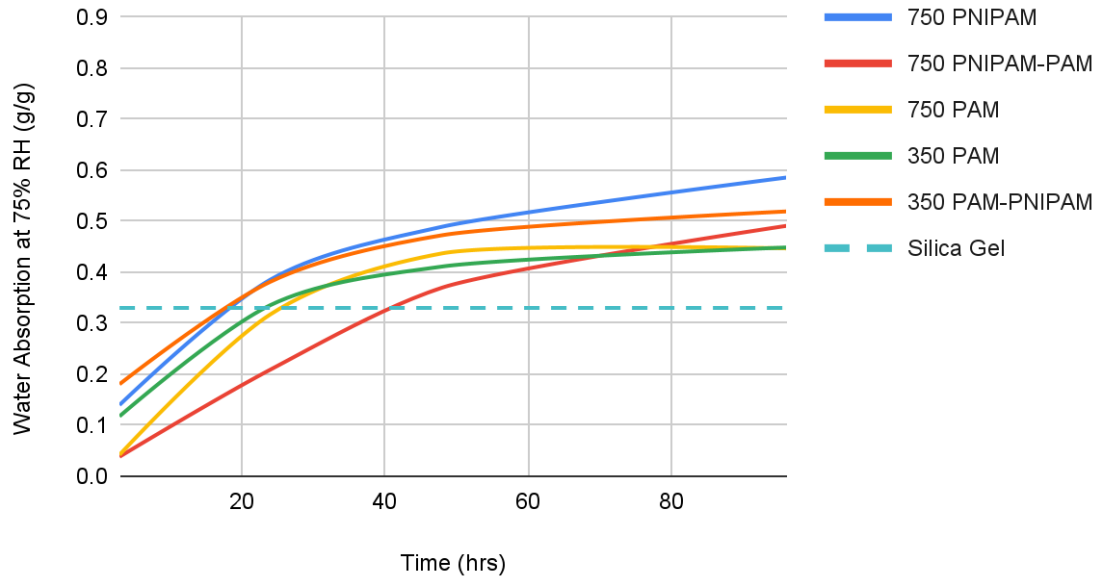
Figure 2: Water absorption of hydrogel composites with 30 wt% $CaCl_2$ and 3 wt% PHS at 75% RH.

We were also interested in the state of the art MOF, and samples with varying degrees of MOF substitution for PHSs were tested. From **Figure 3,** replacing PHS completely with MOF yields an increase of 1g/g in absorption. However, this is not justifiable, given the doubling of the cost (Appendix). This also confirms that 750 PNIPAM is one of the best formulas.
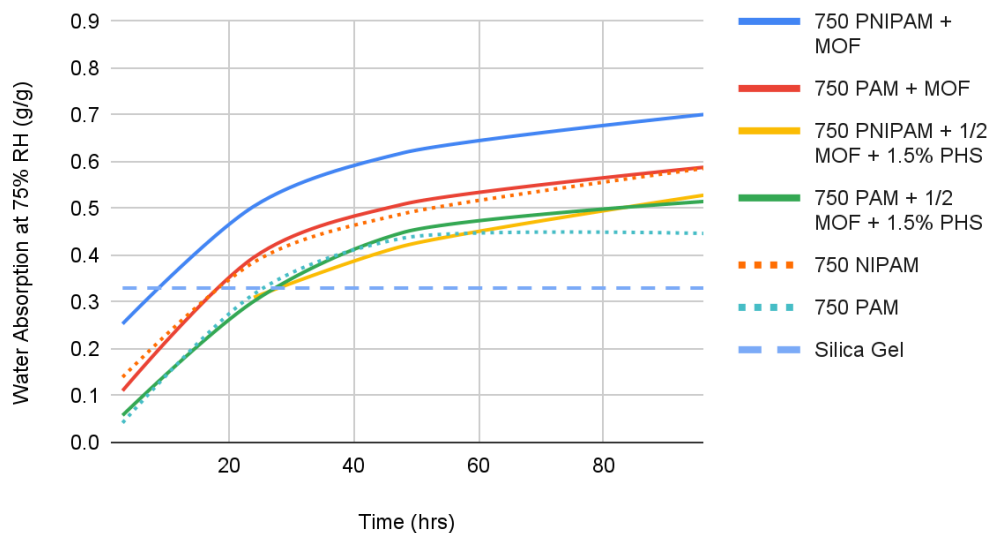

Figure 3: Water absorption of hydrogel composites with 30 wt% $CaCl_2$ and MOF at 75% RH.

750 PNIPAM outperformed 350 PAM-PNIPAM at 75%RH, but when humidity was increased to 90%RH, this flipped, as shown in **Figure 4**. The PAM-PNIPAM blend gained an edge of the pure PNIPAM, likely due to the super-absorbency of the PAM. Near saturations, the superior swelling property of the PAM allows more water to be stored. Hence, the 350 PAM-PNIPAM blend was chosen so that our product can perform at a range of humidity. We also want to exploit the regeneration capacity of the PNIPAM.
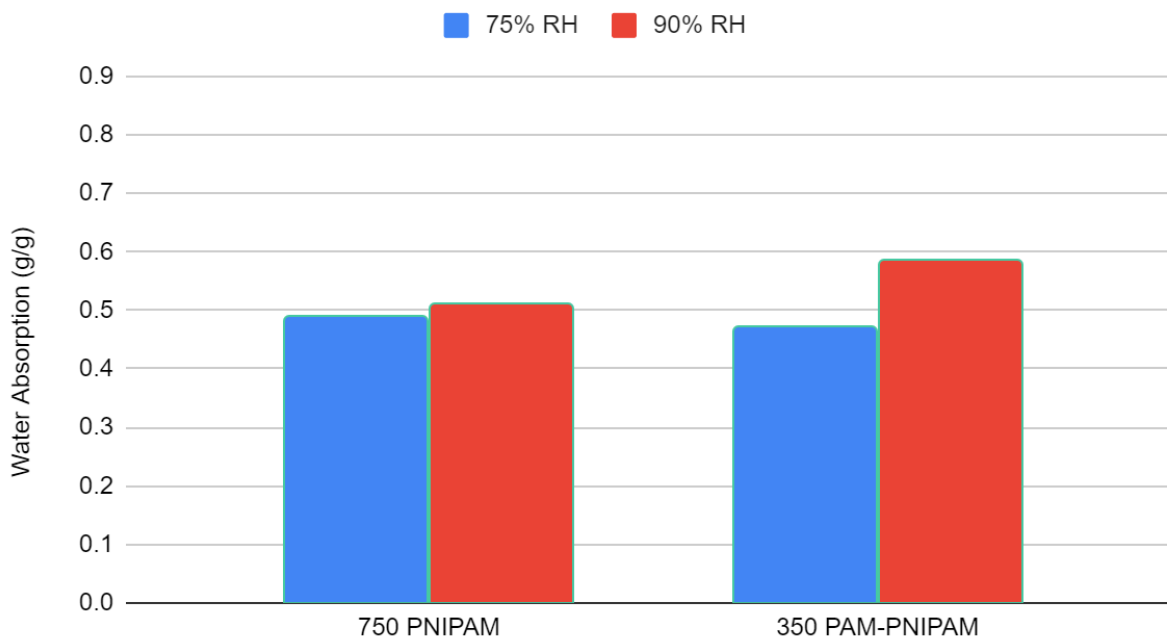

Figure 4: Water absorption of 750 PNIPAM and 350 PAM-PNIPAM, each with 30 wt% $CaCl_2$ and 3 wt% PHS at 75% and 90% RH.

For each hydrogel, varying concentrations of PHS of 1.5%, 3%, and 4.5 wt% were tested. No significant difference in absorption was observed and 3 wt% marginally performed better. Finally, the 350 PAM-PNIPAM blend with 3 wt% PHS were tested with varying salt concentrations. From **Figure 5,** 50 wt% salt performed the best, at 0.89g/g efficiency, almost tripling silica gels. A blend between 350 PAM and 750 PNIPAM was also tested but did not perform as we had hoped.
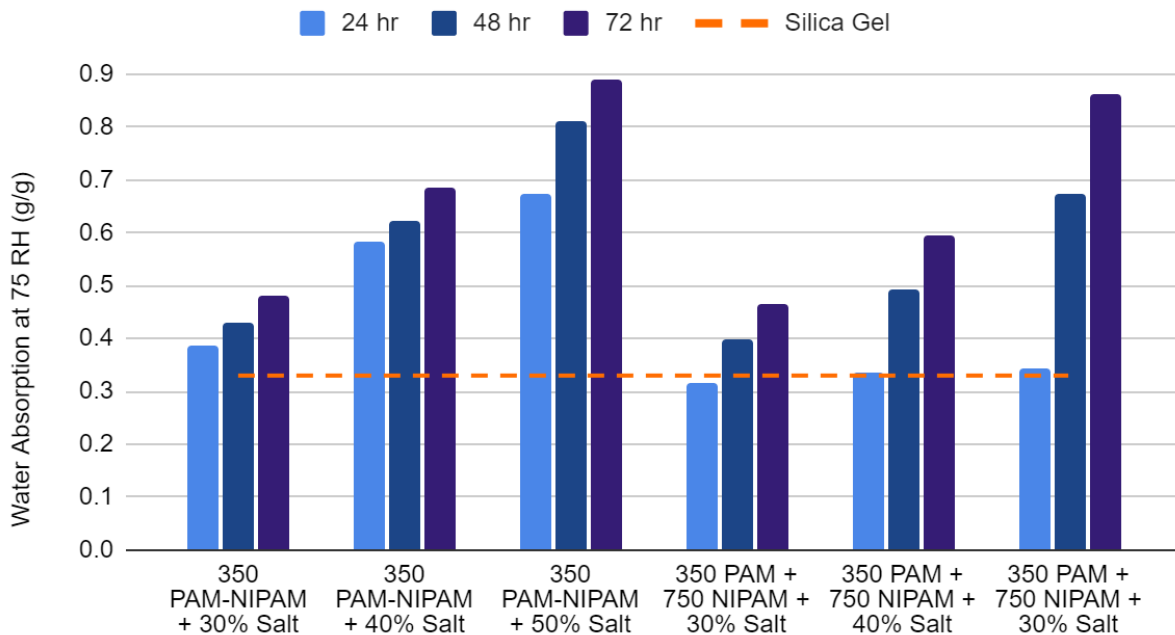
Figure 5: Water absorption for varying salt concentration of 350 PAM-PNIPAM samples at 75% RH.

Cyclic testing of all our samples have also shown a maintained efficiency of 90% over 5 cycles. While further testing is required, we hypothesize that our final product could maintain an 80% efficiency over 15 cycles, since most of the deteriorations actually occur in the earlier cycles, where unbounded salts could leach out. Once all that's left are strongly bounded salts, leaching decreases and we expect a maintained efficiency.

In conclusion, our best composite is a 350 PAM-PNIPAM blend with 50 wt% $CaCl_2$ and 3 wt% PHS. This allows us to exploit the benefits of both the super-swelling PAM and thermo-responsive PNIPAM. PHS is chosen over MOF due to its lower cost and relatively good absorption enhancement.

Adhesion to Kirigami
Adhesion to the PET kirigami substrate was poor when the curing mixture was cast directly onto the substrate without further surface treatment. The coating delaminated quite easily, especially after drying. Oxygen plasma treatment of the surface noticeably improved adhesion by introducing reactive hydroxyl groups to the aluminized surface. The effect of this treatment should be quantified in future work. Other chemistries that functionalize the surface to increase reactivity and improve adhesion further should also be explored.

Application
We envision that our product can be used in 2 ways: a standalone dehumidification screen that can be attached to a window or as an attachment to AC units. Each of the applications can be targeted at a different market segment, allowing Pourgami to maximize value creation.

From our results, 1kg of our best formulation could absorb 0.671g of water vapor (1.42 pints) in a day. An average 10'x10'x10' room at 21°C (70°F) and 80%RH contains only 0.95 pints of water. This shows that we are at the right order of magnitude to make a large-scale impact.

It has also been found that dehumidification accounts for almost 50% of the energy consumption of ACs. By integrating Pouragami into AC units, we could reduce this energy consumption, saving up to $300/year. With 250 million households in India, of which 12% have AC, we can save up to $9 billion annually in energy cost. This will have significant impacts on the economy as well as the global climate crisis.

Conclusion

In conclusion, we have developed two separate material systems using MOF nanoparticles and polymer hollow spheres. Our systems achieve 0.9 g/g water absorption that is 3x better than silica gel, the current industry standard. MOF nanoparticle-infused Pouragami was 20% more efficient than the Dow polymer hollow spheres Pouragami, but the 2x greater cost of MOF Pouragami caused us to choose the Dow Pouragami product, given that we aim to target cost sensitive low-income communities. Our system maintains 90% efficiency over 5 dehumidification cycles in sequence, and is regenerated at 70C, which is achievable with solar collectors. Further directions include investigating alternative thermo-responsive polymers such as methylcellulose that is naturally decomposable to replace PNIPAM and lower our footprint, as well as non-latex hollow spheres that can be recycled.

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Business and Market Analysis

Executive Summary: Pouragami has developed a hydrogel system that leverages the novel geometry of kirigami to capture humidity, targeting tropical, low-income regions that cannot afford AC units and their associated energy costs. Our solution is 10x cheaper than current alternatives and works without any electricity.

Value Proposition: To reach low-income, humid regions by building a low energy dehumidifier that takes advantage of vapor-absorbing materials and highly efficient vapor-material contact.

Stakeholders include not only low-income families that may purchase our product, but also local suppliers. We will source desiccant and hydrogel materials from surrounding regions to cut shipping costs and also bring business to local areas. Furthermore, any new intervention requires education, training, and community stakeholders who are engaged and understand the community needs and belief symptoms. We will require the assistance of medical professionals and community leaders to communicate proper information on the efficacy of controlling humidity in addressing safer living conditions.

Market Research

With 92% without air conditioning among the 2.8 billion people in tropical climates[6] and an average household size of ~6-7 people,[7] there are ~400 million households that need more efficient, cheaper indoor climate control methods. Aside from extreme cases of poverty, the majority of households in these areas currently rely on hand-held, mechanical, and ceiling fans that increase airflow but do not lower humidity levels. All people in these regions regardless of age are severely affected by these weather conditions, though the elderly and those with existing medical conditions are especially susceptible. This market can be expected to remain relatively stable as temperatures rise due to global warming (increasing the number of people in need of efficient dehumidification solutions) and overall wealth of nations increases simultaneously (lowering the market size).

Wet-bulb temperature is defined as the temperature to which the body can effectively cool through evaporative cooling, and is thus the metric of interest. According to the Penn State University H.E.A.T. project study[9] in 2022, wet-bulb temperatures past 88F are considered deadly. Based on data analysis derived from the National Oceanic and Atmospheric Administration (NOAA) Global Surface Summary of the Day (GSOD) dataset[10], the regions with the highest wet-bulb temperature include the Arabian Peninsula, India, and Vietnam, as shown in Figure 1.
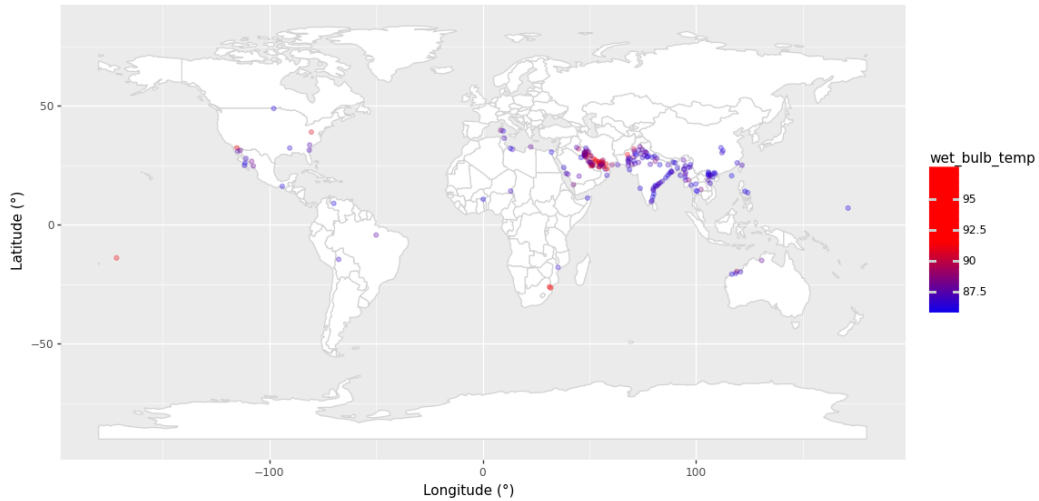
Figure 1. Data analysis derived from the NOAA GSOD dataset that indicates the 200 highest wet-bulb temperatures at weather collection stations around the world. Of the 200 locations, more extreme wet-bulb ratings are shown in red.

In order to gauge low-income need, GDP per capita is plotted against wet-bulb temperatures in Figure 2 using data from the World Bank GDP dataset.[11]
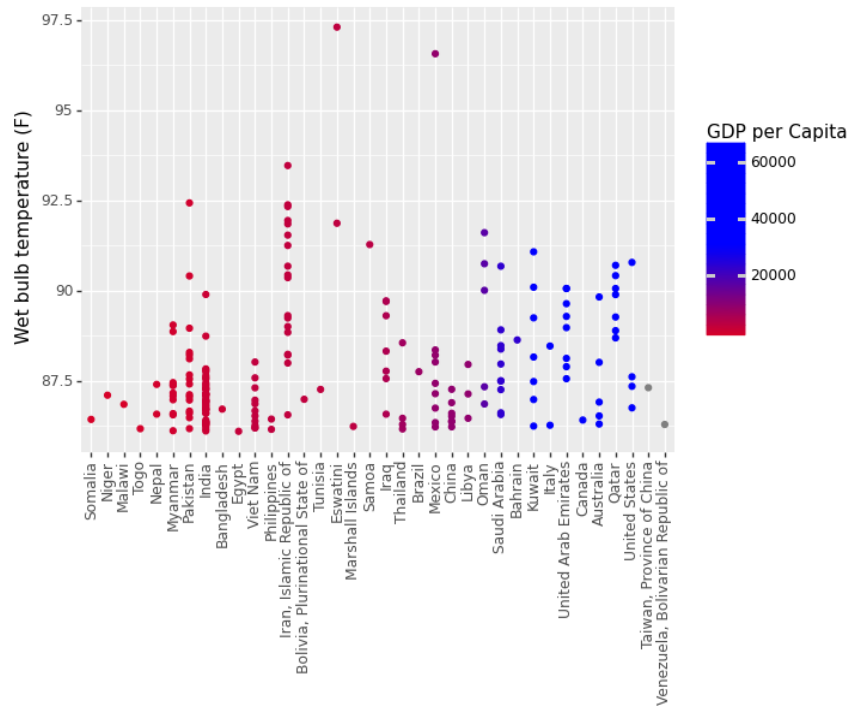

Figure 2. The 200 hottest locations are ranked in order of GDP per capita, with poorer countries on the left. The three poorest countries with the highest wet-bulb temperatures (> 90°F) are Pakistan, India, and Iran.

The three poorest countries with the highest wet-bulb temperatures (> 90°F) are Pakistan, India, and Iran. These countries are the primary target for launching our product. We will target India first, due to the high volume of developmental economic studies in the region, as well as the participation of many non-governmental organizations (NGOs), which will be our outlet into the low-income communities.

Competition

Table I lists existing competitors in hot and humid regions selling products to address indoor climate control in the Arabian Peninsula and tropical Southeast Asia.

Table I: Competitors with products in hot and humid regions targeting indoor climate control

Competitor(s)	Product	Cheapest Option
Daikin Industries Ltd., Midea Group Co. Ltd.	Air conditioning unit	$150/unit*
TCF Azen PTE Ltd., Ferrari Asia Ventilation Co,. Ltd.	Mechanical fans	$15/unit*
Seibu Giken DST	Sorption dehumidifier	$1000/unit [†]
Alrocket, Walmart, Ebay	Household dehumidifier	$50/unit*

*Usage of these climate control methods increases household electricity by an average of 13%.[8]
[†] This method is primarily for industrial applications.

The existing competition does not use novel materials approaches to address humidity but rather systems that require electricity. Furthermore, other than the mechanical fan, each of these options is expensive, and the mechanical fan does not address issues with humidity. Our solution would address the issue of high humidity directly with a materials-centric solution that spontaneously operates without the requirement of electricity. Thus, we cover a significant niche in the market for indoor climate control systems: low income households that must regulate their living conditions due to severe weather climates but cannot afford higher prices or electricity costs.

Costs

The energy costs of AC can be anywhere from $40-60 per month. We have calculated Pouragami's monthly cost to be less than $5. *Figure 3* shows the cost analysis developed, by tabulating the cost of materials through industrial suppliers, as well as the average cost of labor in India.

1. Cost of Materials

MOF Polymer	MOF Nanoparticle					
Component	TMAH (0.1 ml 25 wt%)	Chromium nitrate nonahydrate (0.4 g)	Terephthalic acid (0.166 g)	DMF (5 ml)	ethanol (5 ml)	water (5 ml)
Cost of MOF Pouragami (Bulk)	$3/kg	$150.90/2kg	$877.5/25kg	$850/ton	$1000/ton	$0.03/gal
per unit	0.0003	0.03018	0.0058266	0.004422471712	0.0043486168755	0.00003962582
	Hydrogel					
	NIPAM (0.75g)	mBAm (0.038 g)	Ammonium persulfate (0.023g)	TEMED (45 ul)	CaCl2 (0.34g)	
	$3.25/1kg	$137/500g	$237/2.5kg	$415/2500ml	$320/ton	
	0.0024375	0.010412	0.0021804	0.00747	0.000119931328	
Dow Polymer	Dow Hollow Spheres	Hydrogel				
Component	Dow spheres (0.1 mL 30 wt%)	NIPAM (0.75g)	mBAm (0.038 g)	Ammonium persulfate	TEMED (45 ul)	CaCl2 (0.34g)
Cost of Dow Pouragami (Bulk)	$1.5/kg	$3.25/1kg	$137/500g	$237/2.5kg	$415/2500ml	$320/ton
per unit	0.00015	0.0024375	0.010412	0.0021804	0.00747	0.00011993132

2. Cost of Direct Labor

	MOF Pouragami	
	Probably need 4 people to make samples at same rate as dow	
	Rate: 1 sample every minute	0.012
	Dow Pouragami	Very easy to synthesize, just mix it in
	Need 1 person to make samples	
	Rate: 1 sample every minute	0.003

3. Accumulated Costs

				Total Cost per Month	
Cost of MOF Pouragami	0.05711731441 /unit (5" x 5")				
Cost of Dow Pouragami	0.02576983133 /unit (5" x 5")				
		how many 5"x5" in 4'x4'			
Cost per month for MOF Pouragami	Assume 2 sheets (4' x 4') per month	92.16		$10.53	MOF Pouragami
Cost per month for Dow Pouragami	Assume 2 sheets (4' x 4') per month	92.16		$4.75	Dow Pouragami
	2 sheets means 15 cycles				

*Figure 3. Cost of materials, cost of direct labor, and accumulated costs tabulated, resulting in $10.53/month for an MOF Pouragami, compared to **$4.75/month for Dow Pouragami** (our final product). These calculations assume 15 cycles for each 4'x4' kirigami sheet, and thus approximately 2 sheets used per month.*

Revenue Model

Our revenue model is a transaction-based model that can be considered a mixture of the pay-per-use and subscription models. Since we will market our product through NGOs and community organization leaders as a much cheaper alternative, we will establish connections with retailers in local communities.

Since we aim to target low-income communities, our price must be affordable to spur uptake. Our unit costs are $4.75 per month, and we plan to price our product at **$7 per month for the first 12 months of operation** to support the establishment of our brand and set-up of fixed costs, giving margins of 32%. Past the first 12 months, we will lower our price to **$5 per month**.

Customers will purchase two 4'x4' Pouragami sheets per month at $7 total. Each month, they will return the two used Pouragami sheets to be regenerated to achieve maximum efficiency (and thus leaving no environmental waste or harmful impacts), and purchase two new Pouragami sheets, for a discounted price of $5 total. Thus, our revenues will be at first $7/month per customer and then $5/month per customer, and our costs will decrease over time as we transition from creating new Pouragami sheets to repurposing older ones (resulting in a per-unit cost

reduction of more than 90%, due to the sole costs of only the regeneration salt and labor). Thus, costs per customer per month will be $4.75, and then $0.48 past the first purchase.

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