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Harnessing Technology for Climate Resilience: A New Paradigm in Urban Cooling through Eco-friendly Cooler

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Abstract – Bangladesh is increasingly besieged by severe heatwaves due to the effects of climate change, rapid urbanization, and the pervasive use of heat-generating cooling appliances. While offering temporary relief, conventional cooling methods, such as refrigerant based air cooling systems, are not only unaffordable for most of the population due to their low income but also consume significant energy and intensify the urban heat island phenomenon by releasing heat to the outdoors. The purpose of this work is to develop an innovative, AI-enabled prototype called Eco-friendly Cooler that consists of a metal-organic framework (MOF)-based desiccant dehumidifier, swarm-cooler, and IoT-based sensors to deliver a low cost, sustainable and effective cooling solution based on environmental analysis. A year's worth of data from Dhaka, the capital of Bangladesh, was studied to identify heatwave episodes. As a solution, a prototype is built that can dynamically modulate temperature, humidity, and airflow to generate an optimal indoor environment, ensuring human comfort according to the ASHRAE 55 standard even during extreme thermal episodes without releasing heat to the outdoor environment. Due to its low power consumption, portability, and cost-effectiveness, our prototype will be accessible to a diverse demographic, addressing both economic and environmental sustainability. Our findings propose the widespread adoption of this new paradigm in cooling technology as an appropriate replacement to counter the escalating climatic adversities confronting Bangladesh and other climate-affected developing countries.

***Keywords*:** AI-enhanced cooling, heat island phenomenon, sustainable cooling solutions, environmental conservation, climate resilience, energy efficiency, heatwaves.

1. Introduction

In recent years, major cities of Bangladesh has witnessed a dramatic escalation in heatwaves, exacerbated by the climate change, rapid depletion of green spaces and a surge in air conditioner (AC) usage. This trend has transformed urban areas, particularly Dhaka, one of most densely populated places in the world, into a sweltering heat island, where temperatures soar above the national average almost daily, severely impacting public health, agriculture, and daily life [1].

Amidst escalating global temperatures and frequent heatwaves due to climate-change, Bangladesh confronts the stark reality of high temperature induced challenges. The appointment of a Chief Heat Officer in Dhaka North City underscores the gravity of the situation and the necessity for proactive measures [2]. The conventional solution to indoor cooling is AC, which, although effective, is costly and consumes significant power. Most people in the developing countries cannot afford AC units. Even those who can often find the associated electricity bills prohibitive due to their limited income. Consequently, a large segment of the population suffers during heatwaves due to the lack of affordable cooling options. Additionally, AC units contribute to environmental heat, exacerbating the urban heat island effect [3]. The heat expelled by AC units raises the temperature outside, creating a harsh and uncomfortable environment when people transition from air-conditioned spaces to the outdoors.

Our research presents a comprehensive strategy to mitigate the adverse effects of heat waves, emphasizing both social equity and environmental sustainability. We introduce a novel eco-friendly prototype, which integrates dehumidification, evaporative cooling, and advanced sensing technologies powered by a robust edge computing device that can runs sophisticated algorithms. This prototype is designed to be affordable, scalable, and sustainable, democratizing access to advanced cooling technologies. Recognizing the intricate interplay between climatic factors and urban dynamics, our methodology includes analyzing yearly data to identify the frequency of uncomfortable days. By examining the patterns of temperature, humidity, and airflow variations, we aim to determine optimal comfort solutions. The Eco-friendly prototype is designed to reduce temperature and humidity while enhancing airflow in response to the room's environmental conditions. The proposed appliance is projected to cost approximately one-third of a one-ton inverter AC. Moreover, its power consumption is tested to be one-third to one-fourth of that of a 1-ton inverter AC.

2. Literature Review

A similar project based on an evaporative cooler called cSNAP [4], has been developed by researchers at the Wyss Institute for Biologically Inspired Engineering Lab at Harvard. cSNAP is an indirect evaporative cooling system that utilizes water instead of harmful refrigerants and consumes up to 75% less electricity than conventional air conditioners. This system employs a multi-chambered ceramic heat exchange unit coated with a proprietary desiccant material, enabling it to cool air without adding humidity.

Viguie´ et al. [5] examine adaptation strategies to reduce air-conditioning (AC) energy use during heat waves in Paris. The study uses an interdisciplinary modeling platform to evaluate urban greening, building insulation, and behavioral changes in AC usage. According to the research while these strategies cannot fully replace AC, they can halve AC energy consumption and mitigate heat stress caused by AC systems. J. Christophe et. al. present an IoT-based system for automatic fan control based on ambient temperature. The system improves user convenience, comfort, and energy efficiency through precise temperature measurement and responsive fan control [6]. On the other, our system observe and control fan speed, humidity and temperature to provide maximum comfortable environment. Ramamurthy et al. [7] analyzed the impact of a heatwave on New York City in July 2016, using various sensors to monitor the urban boundary layer (UBL) and surface conditions. They found that the intensity of the urban heat island (UHI) doubled compared to the decadal average, with nighttime UHI values reaching 10°C due to increased thermal storage and a thermal block caused by high-pressure systems.

Another work [8] presents a prototype implementation of a temperature control system in a cooling system using the open-source real-time operating system FreeRTOS and communication via a Controller Area Network (CAN). Utilizing low-cost STM32F407 Discovery Boards with ARM Cortex M4 processors, this prototype is ideal for educational purposes. These studies collectively highlight the advancements I temperature control systems, leveraging IoT, AI, advanced communication protocols to improve energy efficiency, user convince, and environmental sustainability. The advantages of our prototype are manifolds as compared to existing technologies [9]. It is low-cost, AI-integrated, smartly-controlled, adaptable, and still portable. While AC units are fixed installations suitable for single-room use, our portable devices can be moved and used in various locations. Cities and urban areas tend to be hotter than rural areas, especially at nighttime, creating urban heat islands (UHIs). These effects are exacerbated during increased heat waves due to increased absorption and reflection of the sun on concrete compared to green or brown spaces. More of the sun's energy is stored in urban surfaces during the day and released into the atmosphere at night, reducing cooling due to airflow obstruction from buildings and anthropogenic heat release from industry, businesses, and transport vehicles [32].People living in core city areas that are subsequently exposed to the effects of UHI and air pollution are at increased heat-related health risks. Among socio-demographic parameters, vulnerable age groups such as children under five and the elderly over 65 are associated with an increased health risk [33]. Individuals without college degree education have higher death rates during heatwaves. Individuals unable to care for themselves, with limited mobility, or suffering from respiratory, cardiovascular, or neurological diseases are at very high risk of dying during a heatwave. [33] .

Various types of air conditioners exist in Bangladesh, each utilizing different technologies to meet the cooling needs of residential, commercial, and industrial spaces. Window air conditioners are single, self-contained systems installed in windows or through walls. These units utilize a single unit's compressor, condenser, expansion valve, and evaporator to cool and expel warm air outside [10]. Split air conditioners have two main components: an indoor unit and an outdoor unit connected by refrigerant pipes. Split ACs are widely used for their efficiency and ability to cool larger spaces. They employ both inverter and non-inverter technology, with inverter technology adjusting the compressor speed to maintain the desired temperature efficiently [11].

Portable air conditioners are mobile units that can be moved from room to room. They require a vent to expel warm air outside and are similar to window units but designed for portability. They use either a single-hose or dual-hose ventilation system [12]. Central air conditioners are designed to cool entire buildings or large areas. These are more complex systems that consist of a central unit connected to ducts that distribute cool air throughout the space. They often use compressor and evaporator units and advanced thermostat controls [13]. Ductless mini-split systems are similar to split systems but do not require duct-work. They are ideal for homes without existing duct systems or specific zones within a building. These systems use an outdoor compressor/condenser and one or more indoor air-handling units, with inverter technology often a feature for enhanced efficiency [14]. Modern ACs use refrigerants like R-410A and R-32, which have a lower environmental impact than older refrigerants like R-22 [15].

Another popular cooling appliance used in Bangladesh is a Swamp cooler, also known as evaporative cooler. They come in various forms in Bangladesh. However, they work better in regions with lower humidity such as the States of United States-New Mexico, Texas, or Arizona.

Due to Bangladesh's mostly humid climate, another technology is being introduced: dehumidifiers, which reduce uncomfortable sweating. However, they alone cannot create optimum environments due to the persistent high temperatures in the summer. Dehumidifiers used in Bangladesh are typically made from MOF semiconductors [16], ABS semiconductors, and ABS plastic. Key components of a dehumidifier include: Fan, Air Filter, Evaporator Coils, Condenser Coils, Water Collection Tank or Drain, Compressor (for refrigerant-based dehumidifiers), Humidity Sensor, and Control Panel [6].

In Bangladesh, people are mostly interested in ACs but not swamp coolers and dehumidifiers. Swamp coolers are ineffective in high humidity, and dehumidifiers are not widely used due to their cost and size, which are insufficient for even a single room. Various simple or advanced control system used within these cooling systems for ease of use, energy efficiency and automatic controls. Due to ubiquitous of Internet, advanced and newer cooling systems also use an Internet of Things (IoT) component. IoT applications span various domains, including smart homes, smart cities, smart agriculture, smart health, and smart industries. The ability to remotely monitor and control systems and equipment through IoT enhances comfort, convenience, and efficiency [6].

3. Analysis of Heat Related Issues

3.1. Environment Consequence

Air conditioners vary in size and capacity, with a 1-ton AC producing 12,000 BTU/hr or 3.517 kW/h, a 1.5-ton AC producing 18,000 BTU/hr or 5.275 kW/h, and so on, up to a 5-ton AC producing 60,000 BTU/hr or 17.586 kW/h. In Bangladesh, most households use 1-ton, 1.5-ton, or 2-ton air conditioners, while restaurants and offices often use 3-5-ton units [24].

Many people rely on air conditioners during heatwaves without considering their negative environmental impact. These refrigerants, when released, contribute to the depletion of the ozone layer over time. Like other machines that burn fossil fuels, air conditioners emit harmful gases into the atmosphere, contributing to climate change and ozone depletion. Studies predict that by 2050, approximately 25 percent of global warming will be caused by air conditioning [25].

Recent studies have shown that temperatures in commercial areas are 3 degrees higher than in green spaces like Dhaka University and Ramna Park due to the lack of trees and the reliance on air conditioning [26]. Air conditioners were made primarily of mental in the past, but plastic has become more common over the years due to its lower cost and weight. However, plastic is non-biodegradable and harmful to the environment. Moreover, fossil fuels used to power air conditioners are a significant source of global warming pollution. These fuels' extraction, transportation, and combustion generate air and water pollution, emit toxins, and contribute to greenhouse gas emissions. Larger countries produce nearly 117 million tons of greenhouse gas emissions annually from air conditioning, primarily due to low efficiency and high usage of HFC refrigerants [27]. However, they require a constant water supply, which can be challenging in regions with water scarcity. Additionally, they can increase indoor humidity, making them unsuitable for humid climates. On the other hand, dehumidifiers reduce humidity but can slightly increase air temperature. Combining a swamp cooler with a dehumidifier can balance these effects but requires careful energy management [28]. Our proposed prototype will consume less power and ensure a comfortable indoor environment without the harmful environmental impact of traditional air conditioners.

3.2. Cost Analysis and Implications

Bangladesh's dependency on ACs has dramatically increased over the past 12 years. In 2012, 164,000 AC units were purchased, which has risen steadily. By 2021, 208,000 units were sold, nearly doubling to 400,000 in 2022. Last year, in 2023, the number reached 500,000 units [29]. Figure 1 illustrates the growth in AC purchases from 2012 to 2023, highlighting the increasing reliance on ACs, particularly during recent heatwaves, as people perceive ACs as the primary solution for achieving a comfortable environment.

Considering the economic impact, the cost of these 500,000 units, assuming the minimum price of a 1-ton AC in Bangladesh at 45,000 BDT ($390), amounts to 22.5 billion BDT ($200 million). While this expenditure can contribute to the GDP, the energy consumption of these units presents a significant concern. Assuming each of these 500,000 units is a 1-ton inverter AC set at 22°C and used for 8 hours daily, the total consumption would be approximately 3.375 GWh daily, translating to an approximate daily electricity bill of 17 million BDT ($148 thousand). Under the same conditions, a single 1-ton inverter AC would consume about 6.75 kWh daily, resulting in a daily cost of approximately 35.51 BDT and a monthly cost of 1,065 BDT ($9). While this expense is manageable for wealthy and middle-class families, it is unaffordable for lower-income households. Even for some lower-middle-class families, this cost can be burdensome. As of recent data, only 2.28% of Bangladeshi households own air conditioners, up from 1.74% in 2022 [30].

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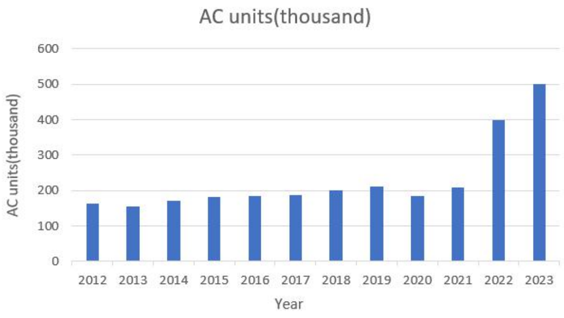

Figure 1: Demand for Air Conditioners in Bangladesh from 2012-2013.

4. Methodology

The proposed prototype offers a sustainable and innovative solution to many challenges that conventional cooling technologies put forward. Unlike traditional AC units, this device maintains indoor comfort through a balanced mechanism that neutralizes the heat it produces, ensuring a smooth transition between indoor and outdoor environments without the harsh contrast typically felt when leaving an air-conditioned room. The system operates in a continuous feedback loop, constantly monitoring environmental conditions and occupant comfort levels. Figure 2 illustrates the design methodology of our prototype, which outlines the functional integration of various IoT devices, a swamp cooler, and a dehumidifier. This system combines these components into a unified prototype, incorporating artificial intelligence (AI) to enable autonomous decision-making akin to an autonomous robot such as modern a vacuum cleaner robot. The major steps for building a prototype are, to select, interface, and develop the firmware for the hardware components, including the Wi-Fi module (e.g., ESP32 nodeMCU), temperature and humidity sensors (e.g., DHT11), transistor based fan controllers (e.g., 2N2222 NPN transistors). To design and test the whole layout for the system using Computer Aided Design (CAD) and Electronic Design Automation (EDA) software. To develop and configure the software of the prototype for controlling and monitoring the system. For example, to program the Wi-Fi module using to receive data from both indoor sensors (in a smart home) and outdoor climate data through the internet.

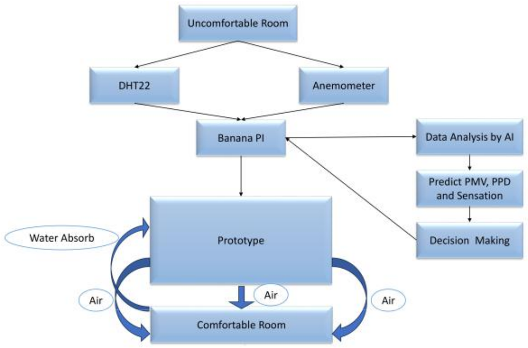

Figure 2: Architecture of the proposed future prototype.

A. Working Methodology

1) Data Collection: The system begins by collecting comprehensive environmental data from the designated room using a network of strategically placed sensors and outdoor climate data. Accurately measures temperature and humidity levels, providing crucial data for analysis. Anemometer: This device measures air flow speed within the room, offering insights into current air circulation dynamics, a critical factor in assessing thermal comfort. These sensors continuously and autonomously monitor the room's conditions, ensuring a real-time data stream to inform the system's decision-making process.

2) Data Analysis: Upon receiving the data stream, the main Micro-controller (e.g., a Raspberry or Banana Pi), functioning as the system's central processing unit, employs sophisticated AI algorithms to analyze the collected data. The AI algorithm meticulously assesses the current temperature, humidity, air flow speed data, and outdoor conditions to establish a baseline understanding of the room's optimal comfort environment. Leveraging historical usage data, environmental parameters, and the ASHRAE 55 standard, the system's AI conducts predictive modeling to forecast the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) metrics [17].

3) Comfort Level Prediction: The system uses insights from the predictive modeling phase to predict occupant comfort levels based on established industry standards, such as the ASHRAE 55 standard [17]. The system considers the metabolic rate of the occupants, as it directly impacts their thermal comfort requirements. Clothing insulation levels influence how individuals perceive and regulate their thermal comfort, a crucial factor integrated into the comfort level prediction process. This data can be deduced from the seasonal data and external climate conditions. Air temperature, radiant temperature, air speed, and humidity are meticulously analyzed to ensure a comprehensive assessment of the room's thermal environment.

5. Testing Methodology

Table 1: Dataset of Dhaka City's Weather Report of 2023.

Month	Uncomfortable Days	Comfortable Days	Max Temp (°C)	Min Temp (°C)	Max Humidity (%)	Min Humidity (%)	Avg Air Speed (m/s)	Sensation
January	28	3	26°C	12°C	95%	47%	0.45	Cold,Insulate,heater
February	10	18	26°C	18°C	88%	53%	0.8	Cold,Insulate,heater
March	6	25	30°C	20°C	94%	58%	0.9	Comfy, Fan
April	13	17	40°C	22°C	92%	22%	0.95	Hot, Humid, AC
May	24	7	38°C	22°C	94%	40%	1.0	Hot, Humid, AC
June	22	8	38°C	25°C	96%	43%	0.95	Hot, Humid, AC
July	25	6	37°C	22°C	100%	54%	0.8	Hot, Humid, AC
August	14	17	37°C	26°C	97%	53%	0.8	Hot, Humid, AC
September	16	14	36°C	25°C	94%	57%	0.9	Comfy, Fan
October	4	27	34°C	23°C	95%	58%	0.6	Comfy, Fan
November	2	28	34°C	18°C	94%	41%	0.4	Comfy, Fan
December	21	10	30°C	15°C	90%	52%	0.3	Comfy, Fan

5.1. Evaluation of Climate Data

To Comprehensively understand the environmental conditions impacting Dhaka, we collected weather reports from 30 different locations across the city, representing a variety of environments, including crowded areas, peaceful zones, riversides, regions with varying levels of vegetation, and areas devoid of water sources [18].

Table 1 complies weather data from the entire year of 2023, gathered from both Bangladesh Government websites and international sources. Using the CBE Thermal Comfort Tool, based on the ASHRAE-55 standard, we evaluated the comfort levels for each month [17],[19]-[23]. This tool considers seven parameters: Cold, Cool, Slightly Cool, Neutral, Slightly Warm, Warm and Hot, with comfort defined by the Slightly Cool, Neutral, and Slightly Warm categories. We fixed the metabolic rate at 1.0 and the clothing level at 0.61 to reflect typical conditions for most Dhaka residents. We determined which months were comfortable or uncomfortable by inputting the maximum and minimum temperatures, humidity levels, and average airspeed into the CBE Thermal Comfort Tool [17]. Months with nearly equal numbers of comfortable and uncomfortable days were categorized as “Average Comfortable.”

Our analysis revealed that out of the 12 months, 5 were comfortable, 2 were averagely comfortable, and 5 were uncomfortable. The uncomfortable months have included the peak heatwave period from April to June and the usually cold months from December to January. This data enables us to infer the likely discomfort experienced inside buildings, houses, and rooms during these periods. This through analysis allows us to infer the indoor discomfort extreme weather periods, providing a basis for developing solutions to enhance indoor comfort in Dhaka.

Theoretical Comfort Analysis: To validate our prototype design theoretically, we utilized the CBE Thermal Comfort Tool, employing the ASHRAE-55 standard method [17]. We fixed the metabolic rate at 1.0 and the clothing level at 0.61 representing typical attire for most Bangladeshis, who often wear trousers and shirts. Considering the current prototype’s inability to control humidity below 50%, we set the minimum humidity level at 50%.

We selected a range of temperatures (31°C, 30°C, 29°C, 28°C, 27°C, and 26°C) and used the CBE Thermal Comfort Tool to determine the comfort levels under these conditions, allowing for local control of airspeed. The results, summarized in Table 2, reflect the optimal comfort parameters for different temperatures while maintaining a neutral sensation. This theoretical analysis provides a foundational understanding of the comfort parameters our prototype aims to achieve. It demonstrates the capability of our device to maintain a comfort thermal sensation across varying temperatures, reinforcing the potential efficacy of our integrated dehumidifier and swamp cooler system in creating a comfortable indoor environment.

Table 2: Dataset of Comfort Weather from ASHRAE-55.

Temperature(°C)	Min Humidity (%)	Max Humidity (%)	Min Air Speed (m/s)	Max Air Speed (m/s)	Sensation
31°C	50%	65%	3	4	Comfort
30°C	50%	70%	1	4	Comfort
29°C	60%	78%	0.7	4	Comfort
28°C	60%	90%	0.9	4	Comfort
27°C	60%	90%	0.2	1.3	Comfort
26°C	60%	90%	0	0.9	Comfort

5.2. Experimental Prototype Testing

We tested our temporary prototype under three distinct conditions: a almost alright room, a fully open room (with natural air from outside), and a fully open room (with natural air from outside and a ceiling fan). Although these tests were conducted during the winter, when the ambient temperature is relatively cool, we anticipate improved performance across other seasons once the AI is integrated and the final prototype is built.

Table 3: Dataset of Prototype Testing.

	Almost Airtight Room			Fully Open Room (Natural Air from Outside)			Fully Open Room (Natural Air from Outside + Ceiling Fan)		
	Temperature(°C)	Humidity(%)	Air Speed(m/s)	Temperature(°C)	Humidity(%)	Air Speed(m/s)	Temperature(°C)	Humidity(%	Air Speed(m/s)
Initial Condition	25.1 °C	80 %	0	24.4 °C	83 %	0 .4	24.7 °C	69 %	1
After Applying Solution	23.2 °C	60 %	0 .2	23.2 °C	60 %	0 .5	23.0 °C	56 %	1
Outcome	Perfectly comfortable			Effectively reduced temperature & humidity			Maintained the temperature & significantly reduced humidity		

In these table 3, this preliminary results from the temporary prototype, which indicate promising performance in regularity indoor temperature and humidity. With integrated AI and enhanced features, we are confident that the finalized version will yield even more effective outcomes, ensuring a comfortable and sustainable indoor environment. The theoretical comfort analysis and our primary prototype testing show that our prototype has performed well during the winter season. With the ongoing summer season and the current heat wave, we continue testing our primary prototype. Once the summer season concludes, we will be able to evaluate the performance of our prototype more comprehensively.

6. Limitations

Our research has several limitations that must be acknowledged. Firstly, we have not yet built our final prototype because we have not selected the type of dehumidifier and swamp cooler that within our cost and capacity range. Some dehumidifiers absorb more water but increase the temperature, while others absorb less water without significantly increasing the temperature but costly. We have also tested our temporary prototype in a fixed room size, which was not adequately enclosed. This limited our ability to control include a mechanism to cool the water automatically, despite survey feedback indicating that users desire this feature. We have tested our device in only two seasons out of all the seasons in Bangladesh. Moreover, we are the uncertain about the performance of cheap Micro-controller such as Banana Pi in successfully integrating AI to make our future prototype smart automated. We also face challenges with the internal circuit design and integration of components using CADs and EDA which require more time. Due to lack of a powerful enough swarm cooler and dehumidifier, our prototype's temperature and humidity control capabilities are not yet fully optimized. For example, instead of reducing the room temperature from 35°C to 25°C, we have only managed to lower it to 29°C. Similarly, our dehumidifier must absorb 3L of water daily but currently achieves only 1.5L at best. Our limitations include selecting dehumidifier and swamp cooler technology, room size and enclosure for testing, precise airflow control, automatic water cooling, seasonal testing, AI integration with Micro-controller, internal circuit design, and financial constraints.

7. Future Work and Potential Improvements

Our future plans for potential improvements are summarized below:

- Optimization of Dehumidifier Technology: Future research should focus on selecting and testing various dehumidifier technologies to identify the most efficient models that balance water absorption with minimal temperature increase.
- Comprehensive Testing in Diverse Environments: Extensive testing of the prototype in various room sizes and types is essential to evaluate its performance in different settings.

- Precise Airflow Control: Future Studies should aim to refine the airflow control mechanisms.
- Automatic Water Cooling Mechanism: Incorporating an automatic water cooling feature into the prototype is a critical next step.
- Integration of Advanced AI Algorithms: It will be crucial to continue developing and integrating advanced AI algorithms with the low-cost cut powerful micro-controller.

Adopting our prototype can significantly mitigate the adverse effects of heat waves in Bangladesh. We can create a more sustainable and comfortable living environment by reducing reliance on traditional AC units and promoting our innovative device, coupled with increased tree planting and widening or creating new water bodies [31].

8. Conclusion

This paper lays the groundwork for developing a more effective and sustainable cooling solution for urban environments in Bangladesh and similar developing countries affected by climate change and human-induced effects due to rapid urbanization. Though modern ACs are suitable for indoor comfort, they are not automatically controlled, are pricey, incur high power usage, and affect the outdoor environment by releasing heat outside. IoT-based smart-cooling devices can control room fans or swarm coolers based only on internal temperature. The effectiveness of these devices during heatwaves and their potential as permanent solutions remains inadequate due to excessive sweating. Our AI-integrated cooling prototype presents a cost-effective, portable, environment-friendly alternative to traditional ACs, fans, or swarm coolers. Its operational autonomy, low operating cost, and portability make it an ideal solution for mitigating the effects of heat waves for city dwellers, ensuring comfort without compromising the outdoor environment. By embracing this technology and promoting other sustainable practices, we can work towards a cooler, greener future for the world facing the daunting effects of climate change and rapid urbanization. However, several components of our prototype warrant further investigation to enhance their efficacy and applicability, which will be the subject of future work.

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